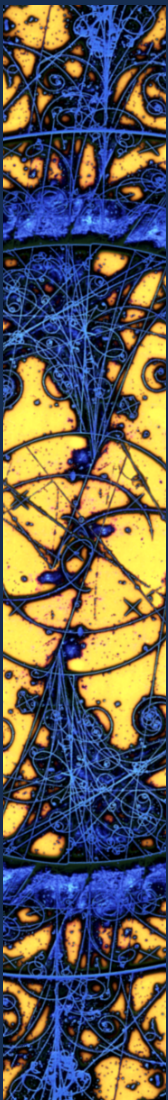
M. VASILYEV and K. STANYUKOVICH

Matter and Man



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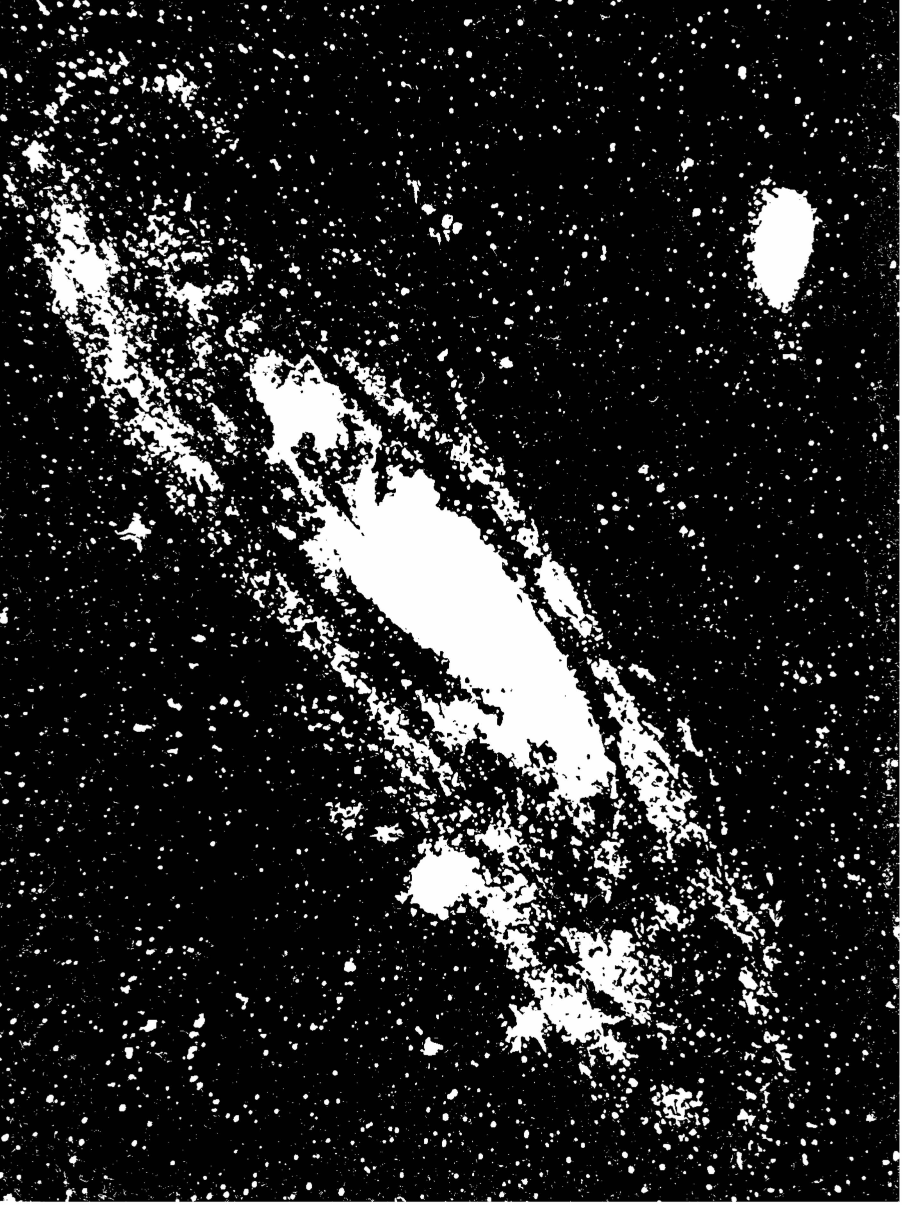

M. VASILYEV and K. STANYUKOVICH

Matter and Man

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М. ВАСИЛЬЕВ, К. СТАНЮКОВИЧ

В мире семи стихий

ИЗДАТЕЛЬСТВО „МОЛОДАЯ ГВАРДИЯ“
МОСКВА

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CONTENTS

Face to Face (instead of an introduction) 7

The Matter of the Universe

A Search for Vacuum 15
States and Fields 25
Man the Master 30
Solids, Liquids and Gases 34

Plasma

The Fourth State of Matter 41
Self-constricting Discharge 46
Stellar Fuel 49

Field

Intangible Matter 59
Omnipresent Force 64
Dr. Einstein's Revolution 68
The Expanding Universe 73
Particles of Gravity 77
In the Heart of the Atom 81
Factories of Matter 83
Continents Awaiting Their Columbuses 85

Machines of Rays and Jets

A Journey Into the Day After Tomorrow 91
Takeoff From the Asteroid Pallas 100

Trip to the Stars . 105
The Time Paradox 110

Explosion

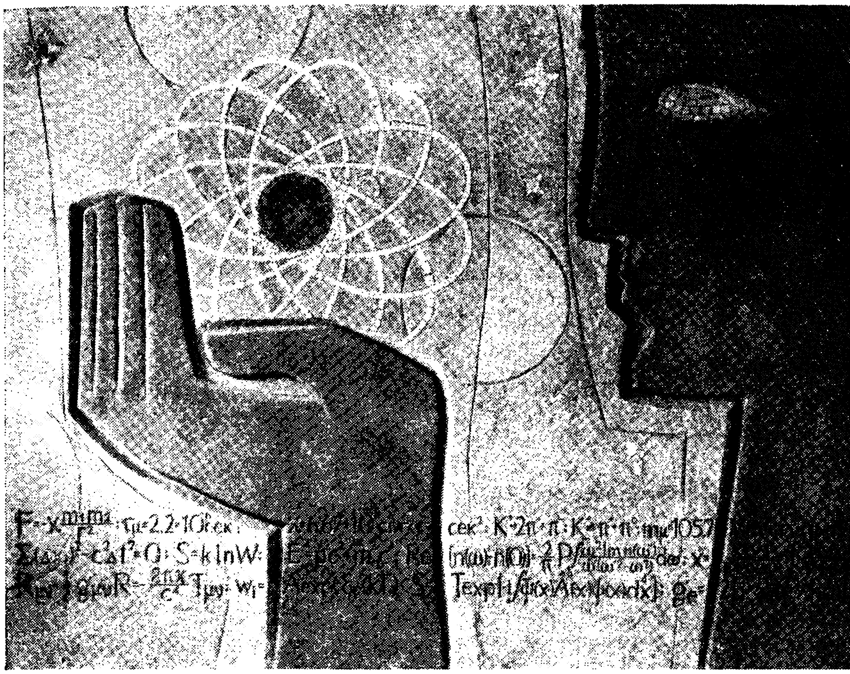
Gas Dynamics 121
Gas Flow into Vacuum 125
Shock Waves 129
Exploding Stars 134
Cosmic Clouds 138
Speed as an Explosive 141
Explosions at Work 144

Biography of the Universe

The Day of Creation 153
The Family of Planets 159
One Turn of the Spiral 163
Masters of the Universe (instead of a conclusion) . 175

Face to face

(INSTEAD OF AN INTRODUCTION)



The world consists of nothing
but moving matter.

LENIN

Millions of people saw the great event in their television screens: a spaceship drifting across the face of the earth, and all of a sudden, a man dressed in a space-suit clambering out of a hatch in the metal hull. After clinging to it for a few moments like a fly to a wall he

pushed himself away and drifted out into the bottomless void, with nothing but a rope like an umbilical chord to keep him from losing himself in the strange, weird world surrounding him. Alexei Leonov, citizen of the Union of Soviet Socialist Republics, first astronaut to leave the shelter of his spaceship and come face to face with the universe. It happened on March 18, 1965. At the other end of the lifeline tied to his suit drifted the *Voskhod 2* space vehicle, a remarkable creation of the human mind and hands. Yet in fifty years or so it will be as hopelessly outdated and clumsy as the bamboo-and-canvas aeroplanes of the beginning of the twentieth century are today.

Leonov had the universe before him in all its glory. The earth in the bluish halo of its atmosphere presenting its continents and oceans like a great geographic globe. The big shaggy globe of the sun, its fierce, blinding radiation unhampered by an atmosphere. Bright untwinkling stars arranged in the familiar patterns of the constellations and shining together with the sun in the black velvety sky.

After ten minutes of breathtaking adventure Leonov pulled himself up to the spaceship by the connecting rope, entered the hatch, passed through the air lock and tumbled into the arms of his friend, commander and fellow astronaut Pavel Belyaev.

The first step has been made. The time is not far off when many more men will come face to face with the universe, infinite and inimitable in space and time, the great universe which knows neither beginning nor end. How much does man know about the universe today, on the eve of his confrontation with it? He lives in a planetary system attending one of the lesser stars in an out-of-the-way part of the galaxy which we call the Milky Way, far from its bright and densely populated nucleus. He lives on the bottom of a rather opaque gaseous ocean enveloping a tiny speck of dust in our galactic island, one of billions of other planets. What can he hope to learn of the universe from his galactic backwoods?

In his short history he has hardly had time enough to take stock of his immediate surroundings. He has only

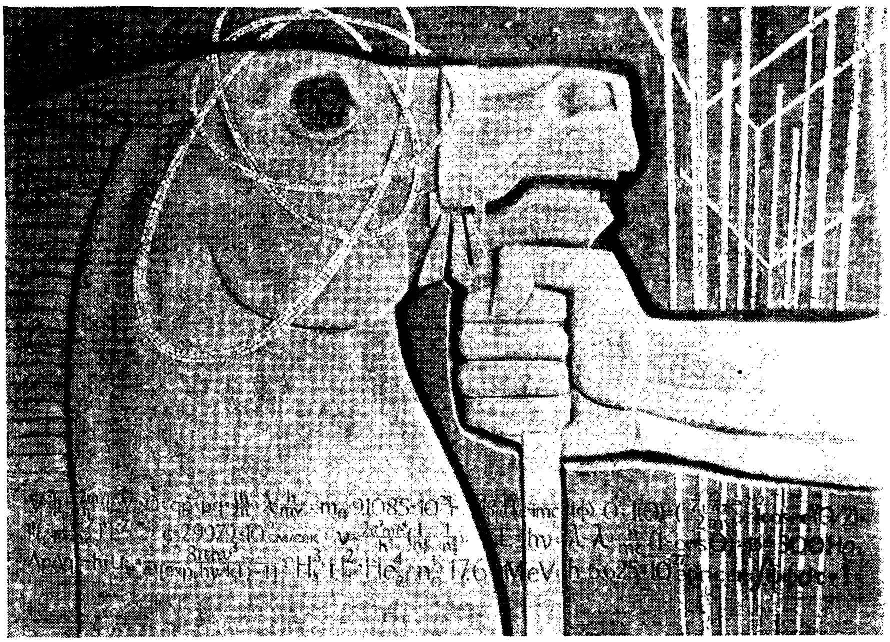
just begun to know and understand himself. The ten thousand years of human civilization are but a fleeting instant as compared with the periods of time in which matter evolves on the universal scale. Less than 450 years have passed since man first proved that his planet is a globe by circumnavigating it. Little more than half a century has passed since he discovered—at first only by speculative reasoning—some of the laws connecting space, time and motion. And he has only just begun to probe the secrets of the structure of matter. Man's knowledge of the universe is paltry indeed and he still has much to learn. But he is inquisitive, and step by step he will unravel all its mysteries.

Poets have compared the stars with the twinkling eyes of the universe looking down on the earth. Man has been looking up at them for thousands of years. Beginning with idle stargazing, he later turned to systematic observations, first with the simplest of implements, today with the help of giant telescopes with lenses several feet in diameter and other sophisticated instruments. He has distinguished the planets from the fixed stars, measured the distances to the farthest nebulae and learned to listen in to the radio voices of clouds of rarefied interstellar gas. His observations to date have been confined to peering through the narrow keyhole of the electromagnetic spectrum to which the atmosphere is transparent.

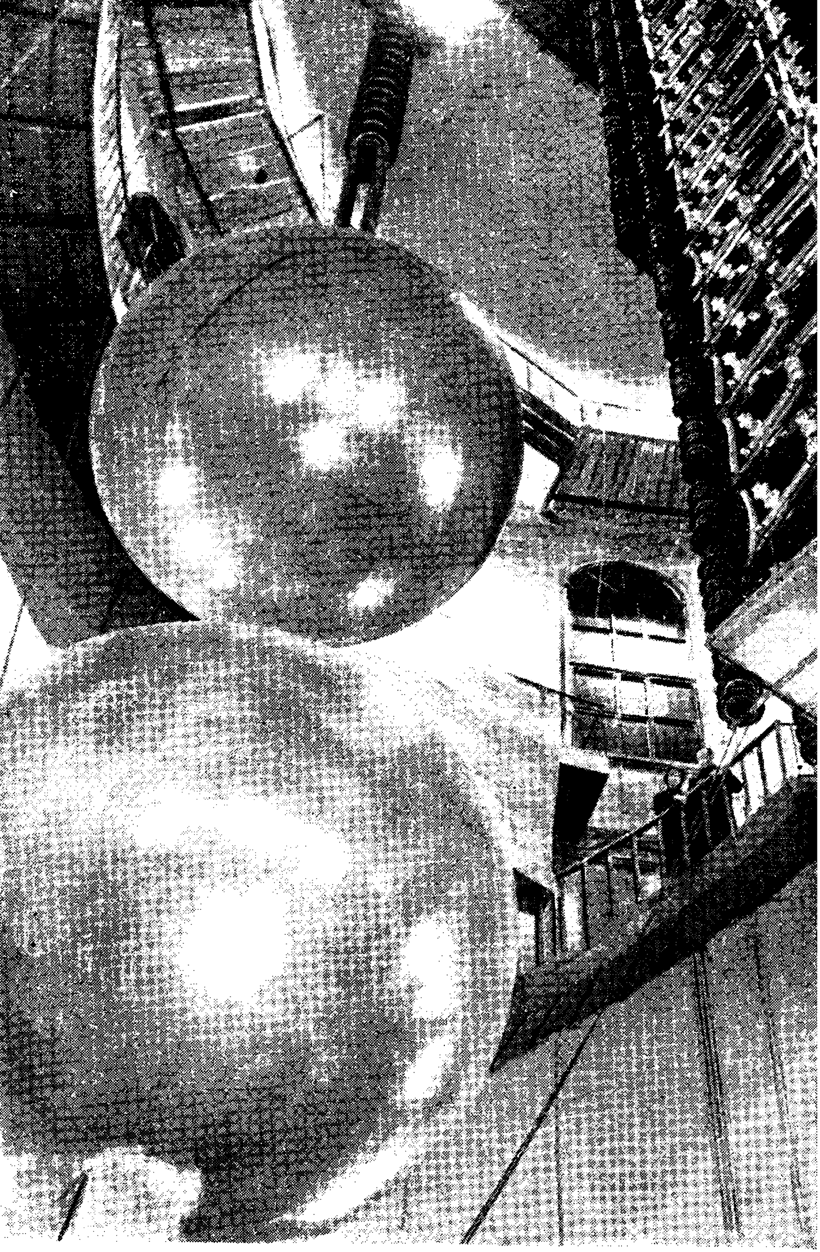
Now man has begun to dispatch mechanical scouts into outer space. He has created the first artificial earth satellites and artificial planets and delivered the first pounds of matter to another celestial body.

Man is calculatingly inquisitive. As soon as he discovers a new law of nature he tries to exploit it for his own ends. Having discovered the secret of lightning bolts he uses it to produce electric light. Having learned the laws of river flow he digs irrigation canals and impounds artificial lakes which affect the very climate of whole regions. He has harnessed the power of nuclear fission of uranium and will soon learn to tame the thermonuclear reactions which heat the sun itself. When he discovers the laws of the universe he will surely put them to work and make them serve him. He will reconstruct planetary systems,

move stars about and regulate their brightness. Man will indeed become the master of the universe, and it will serve him just as terrestrial laws and phenomena are serving him today.



The matter
of the universe



The high-tension gas discharge laboratory of the Krzhyzhanovsky Power Institute, Academy of Science of the U.S.S.R.

A SEARCH FOR VACUUM

When medieval scholars saw that water follows a piston up a pipe they found a simple, though hardly convincing, explanation of the phenomenon: horror vacui. Nature, they declared, simply couldn't stand a vacuum. Then the Italian scientist Evangelista Torricelli demonstrated that it was the pressure of the atmosphere that caused water to rise in the pipe. He measured the pressure and found that it balanced a 10 metre (33 foot) column of water or a 760 millimetre (30 inch) column of mercury. Torricelli took a glass tube about one metre long with one end sealed, filled it with mercury, carefully lowered the open end into a cup of mercury and held the tube upright. Some of the mercury flowed out into the cup and a free space appeared in the upper end of the tube.

"The upper end of the tube," he reasoned, "is sealed off from the atmosphere and no air could pass into it through the glass walls or the mercury. Therefore it must contain a total vacuum."

That was in 1643, and since then the space above the mercury column in mercurial barometers has been known as "Torricellian vacuum".

Today any physicist will tell you that a Torricellian vacuum is not a real, absolute vacuum. For one, it contains mercury vapour. Secondly, there is a sprinkling of molecules of nitrogen, oxygen and even carbon dioxide. These come from the mercury which, like any other liquid, dissolves gases. They readily evolve from the mercury into the high vacuum above the column. The physicist could also tell you of the difficulties which scientists encounter in their attempts to produce and, even more so, maintain a high vacuum. The imperfection of man-made vacuum became especially clear when scientists began sending high-altitude rockets up to take samples of air in the upper layers of the atmosphere. At first glance the job would appear to be quite simple. One had only to take a metal cylinder of suitable size with airtight valves, pump all the air out of it, place it into a rocket and shoot it two or three hundred kilometres* up into the ionosphere, where automatic devices would open the valves, let the outside air flow into the cylinder and close them again. A parachute would carefully bring the sample back to earth.

This, however, is easier said than done. As a matter of fact, it was all the scientists could do to create and maintain a "vacuum" as good as the density of the atmosphere 300 kilometres up. On earth, every material, whether metal, glass, wooden or plastic, contains some gases which readily diffuse into a high vacuum. The process is analogical to the bubbling of gas in a bottle of mineral water. As long as the bottle is closed the pressure inside is above normal, the gas is dissolved in the water and nothing reveals its presence. When you open the bottle the pressure drops and bubbles of gas pop out at the surface. The water appears to boil.

A similar "boiling", though not so violent, takes place in the materials of which a rocket is built by the time

* One kilometre (km) equals approximately 0.62 miles; reciprocally, 1 mile=1.61 km.

it reaches an altitude of 250-300 kilometres. Even in a laboratory, with no end of ingenious devices designed to create an ultrahigh vacuum in a glass or metal cylinder, it is impossible to maintain the vacuum for very long as gases begin to evolve from the cylinder walls, and air even filters through them from outside. So you see that it is not so easy to bring an air sample from a very high altitude.

When Soviet scientists began to study the upper atmosphere they attached jettisonable capsules to a rocket. At the required altitude the capsules (two metres* long and about 40 centimetres** in diameter) were jettisoned clear of the "cloud" of gases exuded by the rocket. The capsules themselves also "breathed", to be sure, but not so much as the rocket.

Can complete vacuum be found anywhere in the universe above the layer of air that balances 760 millimetres of mercury? A trip beyond the atmosphere is necessary to find out, and we shall need a suitable vehicle to embark on such a journey. A balloon, evidently, will not do, for even a stratosphere balloon (or stratostat, as it is called) could take us up only 20 kilometres or so. The gondola would, of course, have to be airtight as at eight or ten kilometres above sea level the air is so rarefied that breathing is impossible. It is obviously ridiculous to speak of vacuum at balloon altitude as a balloon climbs by buoying up in the air just as a cork buoys up in water. Meteorological and radiosonde balloons ascend to 35-40 kilometres, which means that the atmosphere up there is still fairly dense.

Another tangible, and visible, indication of atmospheric presence are clouds. The highest, so-called noctilucent clouds are usually observed at an altitude of about 80 kilometres. Somewhat higher, between 100 and 120 kilometres, meteors appear as shooting stars. A flying meteor is a complex phenomenon involving the interaction of a fast-moving body carrying an electrical charge with the sur-

* One metre (m) $\approx$ 1.1 yard $\approx$ 3.3 feet; 1 foot $\approx$ 0.3 m = 30.5cm.

** One centimetre (cm)=0.39 inch; 1 inch=2.54 cm=25.4 millimetres (mm).

rounding air, and it is proof that the atmosphere is still sufficiently manifest 120 kilometres from the surface of the earth. The aurora polaris (northern and southern lights), which occur in the uppermost layers of the atmosphere, have been observed as high up as 1,200 kilometres.

It goes without saying that neither lighter-than-air balloons nor heavier-than-air aeroplanes can be used for exploring the edge of the atmosphere, to say nothing of outer space. Rockets are the only vehicles suitable for such distant excursions, and high-altitude rockets and artificial satellites have collected much valuable information about the upper atmosphere. It was found that the atmosphere has no sharply defined boundary, and somewhere between 2,000 and 3,000 kilometres up it gradually thins out into the interplanetary gas.

Our quest for a complete vacuum is the first of several distant journeys which the authors have planned for the readers of this book. If you are not of an inquisitive turn of mind or don't care very much for armchair travelling, you might as well shut the book now. If you wish to join company with us, we have prepared a magic vehicle, a dream ship capable of instantaneously carrying us to any part of the universe. Powered by dreams, its launching pad is built on the achievements of science and engineering, its fuel is made up of scientific theories and forecasts, and it is equipped with every kind of measuring instrument which may come in handy for our studies. So all aboard now for our first expedition.

Our first stop is at an altitude of 3,000 kilometres above the surface of the earth, just outside the edge of the atmosphere. A charged-particle counter tells us that this is by no means a vacuum as it records a great number of protons with energies of the order of 100 million electron volts (Mev). These elementary particles have been trapped by the earth's electromagnetic field. They spiral along the lines of force of this field, forming three radiation belts around the earth. (The outermost belt was discovered only recently and not much is known about it yet.) The middle belt is made up of particles with energies of the order of tens of thousand electron volts (Kev). They prob-

ably come from the surface of the sun and remote sources in outer space.

The inner belt, scientists presume, is of a different origin. Streams of cosmic rays bombard the upper layers of the atmosphere. Collisions between the particles from outer space having tremendous speeds and the atoms of atmospheric gases frequently result in the splitting of atomic nuclei. One of the products of such fission is often an elementary particle known as the neutron. Many of these neutrons pass through the rarefied upper atmosphere without encountering other particles and enter the earth's magnetic field. A neutron, as its name implies, is an electrically neutral particle. It does not interact with electric fields, interacts very weakly with magnetic fields and can easily pass through the earth's magnetic field out into space. However, the neutron is an unstable particle, and half of a population of neutrons will normally decay every 11.7 minutes, each decay yielding a proton, an electron and a neutrino. If this happens inside the earth's magnetic field the proton is trapped, as it carries a positive charge and interacts with the field. It is these protons that form the inner radiation belt. The inner belt can be made greater by exploding nuclear bombs in the upper atmosphere or in neighbouring space. An atomic explosion liberates an enormous number of neutrons, which serve as a source of new protons. Other charged particles in the radioactive fallout of nuclear blasts are also trapped by the magnetic field.

Not so long ago, when scientists were still ignorant of the true intensity of cosmic radiation in interplanetary space, it had been feared that it might prove to be so great that space flight would be impossible. Today we know that on the average cosmic radiation is not very intensive and presents no great hazard to space flight. The earth's radiation belts with their high intensity are, however, another matter, and space travellers will have to pass through them as quickly as possible or, better still, skirt them.

There was a time when scientists compared the earth with a large nut encased in a thin gaseous shell. Today we know that the atmosphere extends upward not a few

hundred, but for a good 2,000 kilometres before it trails away into the gas filling interplanetary space. Moreover, the earth is surrounded by a great halo of radiation some 50,000 kilometres in diameter and consisting of charged elementary particles gyrating around the magnetic lines of force. And finally, several years ago the Soviet scientist I. S. Astapovich discovered a gaseous train extending from the earth away from the sun. It owes its existence to the pressure of light which forces minute particles of dust and gas out of the upper atmosphere.

Clearly we must look elsewhere for a total vacuum. We switch on the motors of our dream rocket and leave the cloud of radiation surrounding the earth. Out and out we fly, past the moon, even though we know that it has no magnetic field and is not surrounded by radiation belts. But we remember that instruments on board the Soviet rocket which reached the moon in September 1959 had detected an increase in ionized particles some 10,000 kilometres from the earth's natural satellite. This could be a kind of lunar ionosphere or just a region of higher concentration of elementary particles with energies of several tens of electron volts surrounding the moon. Be that as it may, it is best to seek a total vacuum farther away from cosmic bodies.

The emptiness of outer space, however, is as illusory as the emptiness of a Torricellian vacuum. For one, our

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Mathematically speaking

For the benefit of the inquisitive and mathematically-minded reader, relevant additional information is footnoted to most chapters. Some of the basic laws of nature are elaborated with the help of a few simple algebraical formulas and relationships. No attempt is made to explain the formulas in great detail and their physical interpretation can be gleaned from the body of the chapter concerned. But the reader can use them to engage in calculations of his own. For example, he can compute the mass of propellant that must be "burned" in a photon rocket to achieve a given velocity, or the change in the velocity and pressure of a gas in an explosion, or how celestial bodies attract one another.

These mathematical supplements to the subject matter may help the reader to penetrate deeper into the world of matter, and also develop a thirst for more

instruments tell us that it is pervaded by a tenuous gas with over a hundred molecules in every cubic centimetre. This is not a vacuum! But even if there were no molecules of gas, could we say that outer space is absolutely empty? The answer is no, for it is pierced by the fierce radiation of the sun and of the stars which, though greatly weakened by distance, is readily detectable. We know that light rays, X-rays, infrared and ultraviolet rays—the whole gamut of electromagnetic radiation—are of a material nature and can be treated as streams of tiny particles, photons, possessing mass, velocity and energy. We can hardly regard as empty space through which endless streams of particles pass. Add to this the great gravitational fields which interact in space. Later on we shall speak of this mysterious force of nature. Without going into details, we can note here that gravitational fields are omnipresent. Every material particle, be it a tiny molecule or a giant star, emanates a field of gravity, it attracts and is attracted by other material bodies.

Our dream ship appears to be suspended in the void. Actually, though, it is travelling in an elliptical orbit around the sun. Its motors have imparted it a velocity sufficient to escape from the clutches of the earth's gravity. Had it not been for the gravitational attraction of the sun, earth and planets our vehicle would be travelling in a straight line into infinity. The mighty attraction of the sun, however, pulls the trajectory into a closed curve.

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complicated popular science and scientific books where the various problems are dealt with in greater detail.

WHERE DO COSMIC RAYS COME FROM ?

When electric discharges take place in a medium, charged particles are produced and the medium becomes plasmic. In a plasma an electromagnetic field appears. If conductivity of the plasma is very great and it is at rest, only a magnetic field is produced. A moving medium produces an electrical field.

A magnetic field exerts pressure on a medium. The magnitude of this (internal) pressure is given by the formula,

$$p = \frac{H^2}{8\pi}$$

where H is the magnetic field strength, or intensity, a measure of the energy of the field.

Fortunately, we have an unlimited reserve of fuel and can escape from the sun's gravitational pull. Speaking of gravity, we know that a force can manifest itself only in the interaction of two bodies. A vacuum cannot serve as an intermediary link in any force-transmitting mechanism. Apparently, then, interplanetary space must be pervaded with a material medium which we call a gravitational field.

Out in interplanetary space our instruments record many kinds of particles flitting to and fro. It is hard to call them matter, although when investigated separately they are found to be the nuclei of common elements in Mendeleyev's Periodic System. Especially abundant are nuclei of hydrogen and helium, with a sprinkling of heavier nuclei of nickel and iron. These particles travel with velocities approaching the speed of light, and they are customarily designated as cosmic rays. They, too, inhabit the "vacuum" of interplanetary space.

Interplanetary gas, photon streams, cosmic rays, fields of gravity—this is far from being a vacuum. So out, out, away from the earth and the sun, beyond the orbits of the most distant planets, Neptune and Pluto, out into interstellar space we go. The motors roar and the shackles of the sun's gravitation fall away. The yellow disk dwindles rapidly in the distance until it turns into a plain little star in the boundless starlit void. And still the pens and needles of our instruments quiver and jump as they report their findings:

—molecules of gas, though in smaller quantities than in interplanetary space. Many free electrons as well;

—space pervaded by electromagnetic waves of different length, that is, photons of different energies;

In a unit volume this energy

$$\varepsilon = \frac{H^2}{8\pi}$$

The energy of an electromagnetic field

$$\varepsilon = \frac{E^2 + H^2}{8\pi}$$

where E is the electromagnetic field strength, or intensity.

The particles of a medium subjected to magnetic pressure and acceleration may attain in space (and in laboratory conditions on earth) extremely high velocities approaching the speed of light.

—sensible gravitational fields of nearby stars and the aggregate attraction of stellar clusters around the nucleus of the Milky Way;

—considerable intensity of cosmic rays, only slightly less than in interplanetary space.

Away we go again, out of the Milky Way. The sun is 30,000 light-years from the nearest edge of our Galaxy—that is how long it takes a ray of light from the sun to leave the Milky Way. But our dream ship travels even faster than light (which only dream ships can do) and here we are in intergalactic space. The glowing spiral cloud with two prominent arms in the distance is the Milky Way. Scattered throughout the universe are many other nebulae—galaxies so distant that they appear as luminous dots. We pass an occasional lone star, but most of the stars in the universe are assembled in galaxies and are too far away to be seen.

It is time to switch on our instruments again, but now we must set them at maximum sensitivity. Although the needles quiver at the very zero marks, there can be no doubt as to their messages:

—occasional molecules, atoms and ions of various substances and elements;

—electromagnetic waves from distant galaxies;

—cosmic rays, also from the galaxies;

—perceptible attraction of galaxies considerably weakened by distance.

There is also the possibility of the instruments indicating the presence of some hitherto unknown forces. Latest investigations of galaxies and their positions in space indicate that their strange shapes cannot be explained by gravitational forces alone. From our vantage position we can see some newly discovered astronomical features: some galaxies appear to be joined by luminous "chains", apparently made up of stars; other galaxies are drawn out in rows; some feature strange filaments extending in opposite directions. The impression is that in intergalactic space forces of repulsion predominate over forces of attraction.

In the microcosm, where we have elementary particles and the reactions of decay and synthesis of atomic nuclei,

the dominating forces are nuclear. Going over to the molecular and crystal scale, we find that electromagnetic fields become of decisive importance. With the scale increasing, gravitational fields come more and more into play. They govern the rotation of satellites around planets and of planets around stars. It would hardly be right, therefore, to dismiss as impossible the idea that on still greater scales, involving interactions between galaxies, a new qualitative jump may develop. There is nothing unreasonable in supposing that in intergalactic space there exist unknown forms of matter and fields in keeping with the vast scales that are involved. True, galactic filaments could be explained by the presence of mighty electromagnetic fields, which, unlike spherical-symmetrical gravitational fields, are characterized by cylindrical symmetry (a magnet always has two poles). Be that as it may, but the fact remains that even intergalactic space is not absolutely empty. We must concede that the quest for a truly total vacuum is a hopeless task. We do not know if there is a place in the universe from which no galaxies can be seen. The universe is not homogeneous, and in some directions the number of galaxies appears to be greater than in others. Nevertheless, we may state with utter conviction that it is useless to look for a region of the universe that is completely devoid of matter. For space itself is but a form of existence of matter. Space exists only insofar as matter exists, and in the absence of matter it is meaningless to speak of "space".

The manifestations of matter are extremely diversified. Matter takes the physically "sensible" forms of solids, liquids, gases and plasma (of which we shall speak later on). It appears in the form of electromagnetic, gravitational and nuclear fields. It takes the form of cosmic rays, which can be regarded as both a field and physical material. Many secrets of matter and the interchanges and permutations of its various forms are still unknown to us. But very much is already known. So let us turn our dream ship back to earth. Having failed in our quest for a total vacuum, let us try and answer the question: what is the universe made of, what fills its boundless expanses?

Should one ask a mountain dweller to describe the most characteristic features of the earth, he would most likely say:

"Mountains. Ice-capped peaks rising above the clouds, emerald alpine meadows, narrow, dank gorges with tumultuous mountain streams leaping down them from stone to stone."

A dweller of the plains would offer a different description.

"The earth," he would say, "is a vast plain extending to the narrow strip of the horizon. Terrestrial landscapes are feather-grass billowing in the wind and rivers flowing placidly between low banks."

An astronaut approaching our planet from outer space would hardly be so poetic.

"The planet we are approaching," he would report to his home base, "is covered with a thick layer of water occupying more than 70 per cent of its surface. Dry land accounts for only a little over 29 per cent. Hills and plains are rare exceptions in its physical features."

Our purpose at present is to establish what the universe is composed of. So as not to be in the position of people to whom the earth is either all mountains or all plains we must gain as comprehensive a view of the universe as possible. Scientists have long been wondering whether other planets of the solar system, the sun, the distant stars and extragalactic nebulae are made up of the same chemical elements that we find on earth. In anticipation of the day when earthmen will land on other planets the search for an answer to this question is being conducted in two main directions. Firstly, chemists are studying the composition of extraterrestrial matter that reaches the earth in the form of meteorites. Secondly, astronomers employ special instruments to analyse the spectra of light entering their telescopes which can tell them something of the composition of the bodies that emitted the light.

Meteorites and spectra tell us that the whole of the universe is made of the very same elements as our planet. Only the relative abundances of different elements vary. Stars and interstellar gas consist mainly of hydrogen and

helium. There are thousands of times more atoms of these two elements in the universe than of all the other elements combined. Yet on earth hydrogen is not so abundant and most of it is combined with oxygen in water. Helium, too, is rather rare on earth, and, in fact, it was first discovered on the sun, whence its name.

As for other elements, their relative abundances in stars are about the same as in the earth and in meteoritic matter, though some stars have a preponderance of certain relatively rare elements. The spectra of such stars reveal unusual amounts of lithium, barium, titanium and zirconium. However, they account for not more than one per cent of the total stellar population and are exceptions rather than the rule.

The American scientists Suess and Urey constructed a diagram of the abundances of chemical elements in the universe. They laid off the known elements in ascending order of their atomic weights on the horizontal axis and the relative number of atoms present on the vertical axis. An interesting curve resulted. As could be expected, hydrogen and helium are most abundant. For each atom of silicon, whose abundance was taken as the point of origin of the diagram, there are 40,000 atoms of hydrogen and slightly less of helium. The hydrogen and helium peaks are followed by a steep drop, the abundances of the light elements lithium, beryllium and boron being no greater than one atom each per 100 million atoms of hydrogen. These are followed by a group of elements of about the same abundance as silicon, namely, carbon, oxygen, neon, magnesium and the elements from silicon to calcium. Then comes another sharp drop in the abundances of scandium, titanium, vanadium and chromium. Following them is a rise to the so-called iron maximum: the abundance of iron is about equal to that of silicon. Beyond iron the higher an element's atomic weight the less its abundance. The curve ends with elements whose abundances are hundreds of thousands of times less than that of iron.

In what states are the chemical elements found in the universe and how do they fit into its structure?

Here on earth we find the elements of the Periodic Table in countless different compounds. They constitute all

solid things: the table in your room, the chair you are sitting on, your house, hills and mountains, the terrestrial globe.

On earth we also find matter in its liquid state: water and petroleum, alcohol and mercury. The liquid state is rather unstable. Above 100°C* water boils and turns into steam. Below zero it freezes and becomes solid. If it gets really cold even the mercury in a thermometer may freeze and become as hard as any other metal. But neither is the solid state of iron or gold, granite or basalt, or any other of the substances of which the globe is made very stable. A foundryman heats an open hearth furnace to a temperature slightly over 1,700° centigrade, and iron turns soft and liquefies. He can scoop it up with a dipper and pours it like water. At higher temperatures steel boils and vapourizes. From the conventional point of view, 5,000°C, at which no known substance can exist in either solid or liquid state, is a very high temperature. In the universe, however, much higher temperatures are common. The temperature of the sun's surface is 6,000°, and that of its interior is millions of degrees. Stars have temperatures of tens and hundreds of thousands of degrees.

One of the states of matter is gas. The earth's atmosphere is a mixture of several gases. Chemists tell us that the air we breathe consists of molecules of nitrogen, oxygen, hydrogen, carbon dioxide and other gases.

When the temperature rises these molecules readily split into atoms.

The chemical composition of the upper atmosphere is much the same as at the surface of the earth, though, of course, it is rarefied and has other temperatures. The main thing, however, is that it consists of ions. Instead

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* Temperature in degrees of centigrade (or Celsius, as it is also called), denoted °C, can be converted into degrees Fahrenheit with the formula

$$F = \frac{9}{5} C + 32$$

Zero degree centigrade, the freezing point of water, equals 32°F; the boiling point of water is 100°C=212°F.

of molecules, as at the surface of the earth, there are fragments of molecules which carry electric charges.

We have already made one trip into interplanetary and interstellar space to study the composition of interplanetary and interstellar gas. Our instruments told us that it consists largely of ions, mostly positively charged, and free electrons. Only in intergalactic space did we find whole atoms and molecules of different substances. But the purpose of our excursion was to find a vacuum, and we steered clear of nebulae, clouds of gas and dust, and stars. The number of stars in the universe is infinite. It is estimated that the Milky Way alone contains 100,000 million stars. Huge opaque clouds of dust and gas hide the Galactic nucleus from our vision. The matter of the Milky Way, whose total mass in grams is expressed by a number with 45 digits is, of course, also a part of the universe. In what state does it prevail, at least in our own Galaxy?

Firstly, there is the interplanetary and interstellar gas. Gas rarefied to a degree which in terrestrial conditions would be rated as zero density. Gas consisting of ionized particles and riddled by all kinds of radiation of various intensities. Undoubtedly, masses of this gas must be subject to other laws than those which we habitually apply to terrestrial gases.

Secondly, there is stellar matter. Compressed deep below the surface to pressures which we can hardly imagine and heated to temperatures comparable to those which man has only just learned to obtain in his laboratories for infinitesimal fractions of a second. Inside the stars matter is neither solid, liquid nor gaseous according to terrestrial standards. It is in a special state of which we as yet know very little.

Nevertheless, interstellar gas and the substance of stars have much in common, both being in a state known as plasma. Plasma is essentially very high-temperature matter consisting of free positively and negatively charged particles, it is ionized matter. At very high temperatures chemical reactions are impossible and no molecules of compound substances exist. In plasmas most of the atoms are stripped of their electrons and electron shells. Huge

lumps of dense plasma make stars. Rarefied plasma pervades the whole of space as interplanetary and interstellar gas.

On a universal scale, the conventional solid, liquid and gaseous states of matter are very rare indeed. Solid matter can be found in dust clouds which are observed in the Milky Way. Many stars probably have attendant planets which may be solid, like the earth, though some of the planets in the solar system are believed to be made up mainly of gas. There may also be liquid planets with a solid core of suitable size. But the mass of planets is infinitesimal in comparison with the stars, and the mass of dust clouds is equally small as against the mass of the plasma pervading outer space.

Besides the "ponderable" states of solid, liquid, gas and plasma, matter also exists as fields of different kinds: electromagnetic, gravitational and, in the world of elementary particles, nuclear. Vast regions of the universe, and more likely than not the whole of the infinite universe, are pervaded with mutually intersecting gravitational and electromagnetic fields. Owing to the good conductivity of space, electric fields have a much lower energy than magnetic fields.

Field is a material state of which we probably know even less than of plasma. Fields are invisible and inaudible. For example, our sense organs are incapable of perceiving most of the electromagnetic spectrum, in which visible light occupies a tiny portion. Nevertheless, fields are material and their presence can be detected. Thus, a magnetic field displays itself by directing the needle of a compass along the lines of force. Gravitational fields carry the forces of attraction of "ponderable" matter. Nuclear fields keep the elementary particles of atomic nuclei together.

To sum up. We have visited interplanetary, interstellar and intergalactic space. We have found that the universe is made up of the well-known elements of Mendeleyev's Periodic Table. To be more precise, we ought to say that it is made up of the same elementary particles as terrestrial substances—protons, neutrons, electrons, and others—as most of the universe consists of matter in the,

to us, unconventional state of plasma. Here and there one finds matter in the familiar states of solid, liquid and gas. They are unstable, however, and can exist only in very special conditions which, on the universal scale, are very rare indeed.

Ancient philosophers believed that the physical universe was composed of four basic elements or substances: earth, water, air and fire. Conceptions of the basic elements of nature changed as science developed, and, according to modern views, the universe exists in two basic forms, namely, matter and field. Matter exists in the four states of solid, liquid, gas and plasma; the known fields are gravitational, electromagnetic and nuclear. These are the seven basic elements of nature whose combinations and interactions are responsible for the infinite variety of the observable universe. How has man made the elements of nature serve him?

MAN THE MASTER

The dream rocket we used to look for a vacuum is also a time machine and it can take us back thousands of millions of years into the age of chaos and creation, when the solar system and nature itself as we know it today were in the making. It can also take us thousands of millions of years into the future to see a waning sun and the planets slowing down in their orbits. Our purpose, however, is at present not so ambitious, and we shall travel only a few thousand years back, to the beginnings of human culture.

The hot rays of the sun beat down from overhead. A majestic river flows slowly seawards. Narrow strips of cultivated fields and orchards run along both banks. Beyond them lie endless expanses of sun-scorched desert. This is ancient Egypt, one of the cradles of mankind. We are on the construction site of the greatest of the Pyramids, the Pyramid of Cheops. For scores of years hundreds of thousands of people toiled to pile up 2,300,000 huge slabs of stone weighing some 2.5 tons each. They are laid with such precision that the blade of the thinnest

knife cannot pass between them. An imposing tomb for the Pharaoh over which the millenia are powerless. What titanic machines the builders must have needed to erect it! But we find no machines to speak of, only the simplest of tools: copper and stone cutters separate great slabs from their limestone bed. Masons hew their sides with copper and stone saws, drills and chisels. Teams of ten men harnessed with flaxen ropes, using wooden levers and wooden rollers, transport and lift the blocks hundreds of feet up. Man has undoubtedly mastered here only the solid state of matter.

Up through the ages we travel, stopping 2,500 years later, in the first century A.D. We are in Egypt again, this time in the fabulous city of Alexandria, city of sages, orators and scholars famous, for its great library. Here is a book on "pneumatics", by the remarkable engineer and mechanic Heron of Alexandria. It contains descriptions of many ingenious gadgets and machines. The author had undoubtedly amassed the experience of many scholars before him. Hundreds of years earlier Egyptian temples had probably been equipped with "magic" doors which opened when a fire was kindled on the altar and with "slot machines" for dispensing holy water when a coin was inserted. Water wheels of bamboo had been built in China and India, the most advanced countries of ancient Asia, a thousand years before Heron's time. His *Pneumatics*, however, offered the first descriptions of machines whose operation involved the use of matter in its liquid and gaseous states in addition to the solid one. To be sure, Heron's clever gadgets did not come into wide use. They were toys rather than machines for helping man in his work, and they were soon forgotten. Only the water wheel found wide application. But then, the water which drives an underflow water wheel and the wind which drives a sail boat or a windmill are external forces which man has merely harnessed without changing them in any way. They are not "parts" of the machine but rather the medium in which it operates.

Liquid matter became a working machine "part" only after the French scientist Blaise Pascal discovered, in 1650, the law of pressure transmission in a liquid. The

operation of many types of presses, lifting mechanisms and other machines is based on Pascal's law. Gas and steam became a working machine "part" only after the invention of the "atmospheric" steam engine by the English blacksmith Thomas Newcomen.

And now let us leave our time machine and take a walk in the street of a modern city. Motor cars, omnibuses and trolleybuses drive up and down the street, neon lights flicker in the night, an airplane drones overhead. A car stands parked at the curb. Let us see how matter and fields have been put to work in it. Solid-state matter in the form of metal, rubber, plastics and glass continues to be the backbone of the machine. At the same time engineers have introduced liquid elements. The driver presses the brake and clutch pedals and actuates valves which open or close the flow of liquid. Pistons transmit the force to the brake shoes or shift the clutch disk. Some automobiles have hydraulic clutches in which oil transmits the torque from the engine to the drive shaft. If you study the disassembled engine of a car you will see bore holes piercing the crankshaft, connecting rods and other parts. Their purpose is to deliver lubricant to the working parts. The engine shafts are nested in their bearings with a slight gap which is filled with a film of lubricant. Engineers calculate its shape and thickness in order to use the lubricant as a liquid part designed to reduce friction and remove heat generated in loaded units. We find that an automobile engine actually includes liquid parts.

The pistons in the car's engine are moved by the expansion of a highly heated gas. The hot expanding gases inside the cylinders are as much a part of the engine as the pistons they are designed to move, even though the lifetime of each working gaseous "part" is only a fraction of a second and after each cycle it is ejected through the exhaust pipe. And yet such "parts" work exactly as the engineers designed them to.

Plasma, too, does work in the automobile. The tiny electric spark which jumps between the electrodes of the spark-plug every four cycles to ignite the fuel mixture is a short-lived clot of plasma.

In short, every car driver controls matter in all its four states of solid, liquid, gas and plasma. What about fields? The driver turns the ignition key and switches on the starter which turns the crankshaft even though the piston-driving gas has not yet been formed. The rotation is imparted by the rotor of the starter, which is a small electric motor. After a few simple explanations Heron of Alexandria would probably have quickly grasped the principles of operation of the hydraulic clutch, the hydraulic brakes and even the engine. But he would hardly be able to comprehend the nature of the forces responsible for the rotation of the rotor of the electric motor. He would find no observable force being imparted to it, no moving rigid rod, no liquid flow, no expanding gas. Heron had not the slightest idea of such things as fields of force. Today we know that when a driver switches on the starter of his car he brings electromagnetic fields into complex interactions which result in the rotation of the rotor. Incidentally, the beam of light running ahead of the car on a dark road is also a representative of the electromagnetic field. The music in the car's wireless set, too, has been carried from some distant broadcasting station by an electromagnetic field. Today electromagnetic fields serve man faithfully, yet hardly 150 years have passed since the time of the first practical application of electricity, when Pavel Schilling set up a telegraph line between the Tsar's Winter Palace in St. Petersburg and the Ministry of Transport (not taking into account, of course, the light of a fire or paraffin lamp, which is also due to electromagnetic field). Only a few of man's machines incorporate tamed nuclear fields, and gravitational fields are yet to be harnessed.

Man is indeed master of nature. His mastery over solid matter has increased immeasurably since the days when the Great Pyramids were built. He has created new substances to suit his needs: steel and artificial rubber, plastics, silicons and other substances. He has discovered and put to use such hidden secrets of matter which scholars of yore could never even have dreamed of: piezoelectric crystals which "talk" and "sing" owing to their property of expanding and contracting under the appli-

cation of an electric field; pure silicon which transforms sunlight into electricity; radium which appears to generate light and warmth out of nothing. Man has learned to use the properties of liquids, and he has built hydraulic presses, turbines, transmissions and servomechanisms in which liquids are put to work. He has found applications for gases and steam in steam engines and turbines, pneumatic couplings and brakes, drills and power tools. Harnessed jets of gas turn the propellers of gas-turbine aircraft and carry rockets into outer space.

The applications of plasma are as yet not so great: the cold glow of luminescent lamps, electric sparks in spark erosion machine tools, arc lights, mercury rectifiers. Our knowledge of the secrets and laws of plasma is fragmentary and its taming is a thing of the future.

Even worse is the state of affairs in respect of fields of force. Only the electromagnetic field has really been studied and put to work. Nuclear fields have been put to work in atomic power plants, in nuclear-powered ships like the icebreaker *Lenin*, in the radium-luminescent indicators of precision instruments and the cobalt guns used for treating malignant tumours. And almost totally unused are gravitational fields. Fields of force have yet to unfold their secrets before man.

SOLIDS, LIQUIDS AND GASES

The deeper the man penetrated into the laws governing solids, liquids and gases the more he found in common among them. What are the main differences between these three states of matter?

Solids possess definite volume and definite shape, that can be altered only by the application of a force, which in some cases must be very large.

Liquids possess only definite volume, but not shape. In terrestrial conditions liquids generally take the shape of the vessels which contain them.

Gases possess neither volume nor shape, and they occupy the whole volume of the vessel containing them.

The differences are apparently great, yet in some conditions matter may behave in ways which seem incompatible with its state. Marble is hard and brittle, yet under a pressure of several hundred thousand atmospheres* it begins to flow like a liquid. Iron, too, may flow, or creep, under sufficient pressure. Under high pressure the forces causing the displacement of atoms are greater than the forces keeping them together in the crystal lattice. The bonds within crystals, which are of an electrostatic nature, collapse and the atoms start behaving independently, as in fluids.

On the other hand, a gas can be compressed to a degree when, at relatively low temperatures, atomic cohesion forces come into play and the gas acts like a solid, while remaining a gas.

A jet of water from a firehose nozzle rises vertically like a solid bar, without scattering a drop. If you strike it with a wooden stick you may knock a few drops out of the jet, but you may also break the stick as if you had hit an iron rod. Powerful jets of water are used in hydraulic excavators. An electrically driven pump delivers water at a pressure of 6 to 20 atmospheres to the nozzle of the excavator. The thick glittering jet of water cuts through

Mathematically speaking

BERNOULLI'S EQUATION

Bernoulli's equation describes the steady flow of a fluid, which is independent of time. The equation proceeds from the consideration that, neglecting energy losses due to internal friction and heat exchange between different parts of a flowing fluid, the total energy is the same for any cross section of the stream. The energy may change from one form to another, but the total does not change.

In what forms does energy exist in a flow of gas, for example, through a pipe? Firstly, the kinetic energy of motion, denoted E_k. For a unit mass

$$E_k = \frac{u^2}{2}$$

where u is the velocity of flow.

Secondly, potential energy. If a gas is under pressure, in expanding it can do work. Denoting potential energy by

* One atmosphere (atm) is the normal pressure of the air at sea level; 1 atm=1 kg/cm^2=14.7 lb/in^2.

soft rock like a knife through butter. A skilled operative cuts out chunks of rock, slices them to pieces and washes them away. Hydraulic excavators are even used to mine coal. One should not think, however, that the molecules of water in such a "solid" jet are joined by the bonds one finds in solids. Here the liquid remains a liquid and its remarkable properties are due to the high speed of impinging.

If in some circumstances solids and gases display similar properties, the similarity between gases and liquids is evidently much greater. This can be seen in the facts that liquids and gases are frequently joined under the common heading of fluids, which obey the same laws, and that devices designed for the utilization of the properties of liquids or gases have much in common. There seems to be a great difference between a submarine and a dirigible. Yet both are based on Archimedes' famous law, which states that *any solid body submerged in a fluid is subject to a buoyant force equal to the weight of the fluid displaced by it*. The obvious conclusion is that if a body is lighter than the fluid it displaces it will ascend in the medium. In this way submarines rise to the surface by pumping water out of their ballast tanks. In this way balloons and dirigibles float up to considerable heights in the air. This, too, is the principle employed in the bathyscaphe, a deep-sea exploration vessel resembling a submarine with

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the symbol E_p, for a unit mass of the gas

$$E_p = \frac{k}{k-1} \frac{p}{\rho}$$

where p is the pressure, and ρ is the density of the gas, and $k = \frac{C_p}{C_v}$ is the ratio of the heat capacities of the gas at constant pressure and constant volume. For air $k = \frac{7}{5}$.

Thirdly, a fluid possesses potential gravitational energy. If a gas flows up in a tube, its gravitational energy increases with height. Denoting the potential gravitational energy of a unit mass E_g, we have:

$$E_g = gh$$

where h is the elevation, and $g = 9.8$ m/sec^2 is the acceleration of gravity at the surface of the earth.

Bernoulli's equation states that the sum of these three

a spherical steel chamber attached to its bottom. The chamber is provided with observation ports covered with quartz and capable of withstanding the tremendous pressure of the water. The ballast tanks of the bathyscaphe are filled with petrol, and iron ballast is attached to the bottom by means of powerful electric magnets. The bathyscaphe with its crew and ballast weighs more than the displaced water, and it sinks to the bottom of the ocean. The record depth attained by bathyscaphe is 35,300 feet.

An airplane would seem to be far removed from an ocean liner. Yet an airplane propeller and ship's screw are based on the same principles, as are also the rudders of both kinds of craft. Formerly water craft did not have wings. Now ships on underwater wings, or hydrofoils, are being built. When it is moored fast a hydrofoil craft, as it is called, looks much like any other ship. But when it moves it rises on its foils. The motion of the foils through the water generates the same kind of lift force which supports an aircraft in flight. It elevates the ship's hull out of the water, thereby considerably reducing the resistance and, consequently, increasing the speed.

Man's main power-generating machine is the turbine —hydraulic, steam and gas. At first glance they do not appear to be very much alike, and a nonengineer would not readily be able to point out the common features of, say, a hydraulic and a steam turbine. But their blades

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forms of energy is constant for a given fluid flow, viz.:

$$E_k + E_p + E_g = \text{const}$$

For unit mass this expression yields:

$$\frac{u^2}{2} + \frac{k}{k-1}\,\frac{p}{\rho} + gh = \text{const}$$

From this equation a number of interesting conclusions can be drawn. Suppose that a gas is flowing through a pipe of varying diameter. Its mass must evidently remain the same, whence

$$\rho u s = \text{const}$$

where s is the cross-sectional area of the pipe.

If the motion takes place adiabatically, that is, without heat input or dissipation, the following relationship between pressure and density holds:

$$\frac{p}{p_1} = \left(\frac{\rho}{\rho_1}\right)^k$$

where p_1 and ρ_1 are the initial pressure and density, respectively. This is Poisson's adiabatic

work according to the same laws, only in the case of the hydraulic turbine momentum is imparted by noncompressible water and in the case of the steam turbine, by expanding steam. Incidentally, in many calculations engineers and scientists neglect the compressibility of air and treat it as a very light liquid. In short, in spite of their substantial differences solids, liquids and gases have very much in common.

And what about plasma? Do any of its properties resemble those of solids, liquids and, especially, gases, which it seems to resemble most?

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equation. One can use it to determine the speed of sound, a, in a given medium:

$$a^2 = \frac{kp}{\rho}$$

In the horizontal motion of a fluid, $h=\text{const}$, and Bernoulli's equation takes the simple form

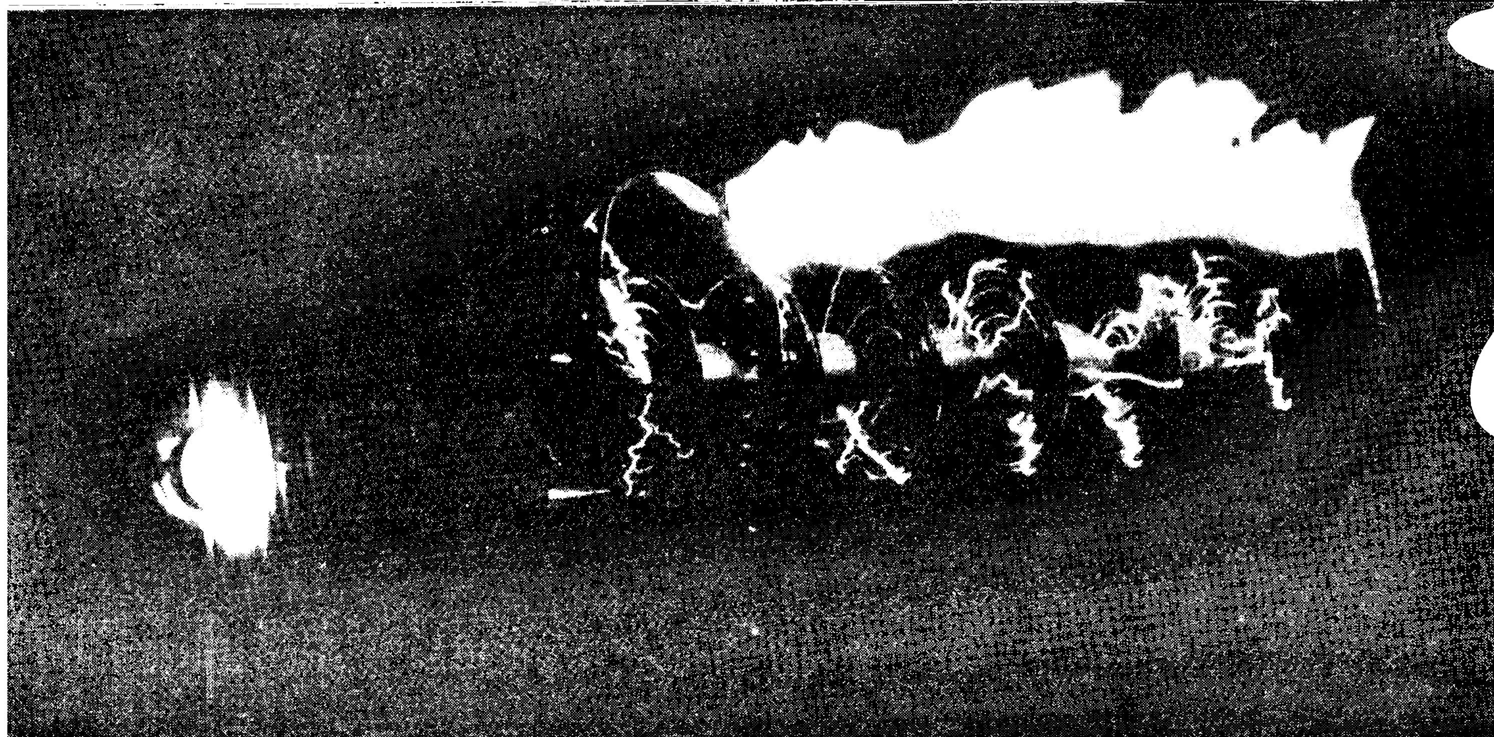
$$u^2 = \frac{2}{k-1}(a_0^2 - a^2)$$

where a_0 is the speed of sound in the stationary fluid.

Imagine now that a stream of gas flows past an aircraft wing. The part of the stream passing over the wing must move faster than the part passing below so as to cover the distance from the leading to the trailing edge in the same time. But the faster a fluid moves the lower the pressure in it. Therefore above the wing there develops a region of lower pressure, which "sucks" the wing up. This is how the lift force of an airfoil develops.

Bernoulli's equation varies for compressible and incompressible fluids (when $k \to \infty$ and $E_p = \frac{p}{\rho_0}$), and its members may be expressed in terms of different physical quantities.

Plasma



A high-voltage discharge

THE FOURTH STATE OF MATTER

When speaking of plasma one should always specify the kind of plasma one has in mind. As mentioned before, plasma is a mixture of ionized atoms (ions) and free electrons, with a greater or lesser sprinkling of whole atoms, and sometimes even molecules of gas.

Although all gases, including the air we breathe, always contain some ionized atoms and free electrons, the properties of plasmas differ markedly from those of gases. In plasmas the atoms are in an excited state, a continuous exchange of electrons takes place between them, and ions and electrons collide continually in the course of their random motions. These processes are accompanied by the emission of photons, which are responsible for the glow of plasma. Gases, of course, do not ordinarily glow.

The simplest type of plasma can be produced by merely striking a match. The little yellow flame is a plasma. Air is a dielectric, which is to say that normally it does

not conduct electricity. This property of air, incidentally, is utilized in the variable capacitors with which one tunes in to a radio station on a radio set. Plasma, on the other hand, is an excellent conductor of electricity.

Plasmas need not necessarily be associated with high temperatures. The glow of highly rarefied gas in a fluorescent tube is also due to plasma, yet the tube is hardly warm to the touch. However, if temperature is defined as the average kinetic energy of the particles of a medium, which is given by their velocities, the plasma in a fluorescent tube has a high temperature. The electrons and ions travel inside the tube with velocities corresponding to temperatures of thousands of degrees (actually, the light electrons move faster than the heavier ions, whose greater mass offers greater resistance to acceleration). Why then, one might ask, doesn't the glass tube containing such high temperatures melt? The reason lies in the rarefaction of the plasma. The impacts of ions and electrons are much too infrequent to transmit much energy to the walls.

Temperature measurements of the upper atmosphere carried out with the help of rockets and artificial satellites revealed layers of gas heated to 500, 800 and more degrees centigrade. It would appear that the earth is surrounded by an incandescent cloud of gas which would heat up a spaceship passing through it. This, however, is not the case, and the atmosphere up there is so rarefied that it could heat a body to only a few degrees above absolute zero. In the upper atmosphere a body's temperature is determined largely by the radiation of the sun and earth.

The temperature of a match flame is not very high as compared with the temperature of a gas torch, burning fuel in the cylinder of an internal-combustion engine, the jets in the nozzle of a rocket motor or the explosion of dynamite. Accordingly, higher is the degree of ionization of the gases involved and the "purity" of the plasma.

The upper temperature limit of chemical reactions is of the order of 6,000-8,000 degrees. Beyond that boundary the "true" state of plasma sets in, a state which is still very poorly studied since we can produce somewhat higher temperatures in laboratory conditions for only very brief periods of time.

In one experiment a powerful current was made to pass through a thin wire joining two electrodes. The wire instantaneously vapourized, the vapour that had not yet expanded continuing to conduct the current for a few instants, which raised its temperature still higher. The tiny cloud of plasma thus produced had a temperature of around 8,000°C, about 2,000 degrees higher than the surface of the sun.

A device for obtaining temperatures of the order of several tens of thousands degrees is the shock tube. In a tube filled with rarefied gas a shock wave moving at ten times the velocity of sound can heat the gas to a temperature of 3,000°. Higher velocities yield higher temperatures. These are about the only known methods of producing plasmas at temperatures below the 10,000-degree range. No scientist has yet been able to study the range between that mark and the neighbourhood of one million degrees.

Higher temperatures have been achieved by Soviet scientists by an ingenious method elaborated by A. Sakharov and Igor Tamm, members of the Soviet Academy of Science, which we shall speak of later on. Beyond these temperatures lies another infinite *terra incognita*. Superhigh temperatures of this order occur frequently enough in nature in conditions which preclude the study of matter. Stellar surfaces have temperatures of 6,000 to 20,000 degrees and even higher. The temperature yield of a nuclear explosion is around one million degrees. The temperature inside the sun is more than a million degrees, and possibly as high as 10 million, and inside the hottest stars it is probably thousands of millions of degrees. These are temperatures at which, physicists consider, the creation of nuclei of iron, titanium, manganese, cobalt, nickel, copper and zinc takes place. However, the superhigh temperatures inside stars do not permit us to study the properties of matter under such conditions.

Many scientists are engaged in the study of high-temperature plasmas ranging from 10,000 to several tens of millions of degrees. One of the devices for producing plasma jets represents a cylinder with a graphite plug having a hole in the middle at one end, and a graphite electrode passing through the other end. The positive pole of a source of electricity

is connected to the cylindrical electrode, and the negative pole to the ring electrode. When the current is switched on an electric arc develops inside the cylinder and a jet of plasma up to two feet long issues from the hole. The plasma generating mechanism is as follows. Application of a potential difference to the two electrodes produces an electric field. The free electrons that happen to be inside the apparatus are rapidly propelled towards the positive electrode. When such an electron strikes a molecule of air it splits the molecule into two ions and liberates several new electrons, which also collide with the atoms and molecules of the air in their motion towards the anode. The air inside the cylinder rapidly turns into a stream of plasma in which electrons are flying rapidly towards the anode and slower ions are moving towards the cathode. The collisions grow more frequent, the temperature rises and the plasma begins to glow. When the temperature rises so high that positive ions are ejected from the surface of the anode an electric arc with a flame temperature of around 4,000° develops. This, of course, is more than the material of the cylinder can stand. To cool its walls cold air is blown inside the cylinder and it compresses the plasma into a thin, highly conductive column which is called a plasmic pinch, through which current flows at a high rate. The temperature rises still higher and the plasma is further constricted by the "pinch effect" of its own magnetic field: invisible magnetic rings compress the plasma like rubber banks and a dense jet of incandescent ionized gas issues through the hole in the front wall of the apparatus in a blinding thin blade. This is a real plasma, in which practically all the atoms are ionized and whose structure is determined largely by its own electrical field.

The described apparatus finds many industrial applications. It can be used in metallurgy, building, mining and other fields. Plasma jets can cut steel like a hot knife cuts butter. They can drill holes in hard rock faster than the best diamond drills. They can be used to melt and cast highly refractory metals, such as tungsten, which no one has ever seen in liquid form.

Industrial plasma torches that operate on the principle described above have been produced by the Baikov Metal-

lurgical Institute in Moscow. They are simple in manufacture and operation and require no special auxiliary equipment. Such a torch can make a very smooth 3-mm slot in a 15-millimetre plate of stainless steel that almost entirely resists oxygen-flux cutting. Plasma jets can be used to weld thin stainless steel sheets. The mechanical properties of the seam hardly differ from those of the metal itself. A plasma torch can shape metals and cut extremely smooth grooves. It can be used for applying coatings, in which case the coating material is introduced into the gas stream in powder form or simply by placing a rod of the material in the jet. The plasma cutters are being manufactured commercially and used along with other metal-cutting machine tools.

During World War II, the Soviet scientist Professor G. I. Babat carried out a series of experiments with plasma rings which, he found, behaved much like ball lightning. Similar experiments were later conducted on a larger scale by American scientists. One of the methods of producing a plasma ring requires a device looking like a thimble, and just as large. Two electrodes of titanium saturated with hydrogen are passed through the closed end of the thimble and an electric pulse is applied. An electric arc springs between the electrodes. It expands in a semicircle of plasma which then detaches, closes into a ring and shoots off at a velocity reaching 200 kilometres a second. This is ten times faster than a rocket launched into outer space. In vacuum, plasma rings display some remarkable properties: they pass practically unaffected through magnetic fields; upon impact two rings most frequently rebound like rubber balls; when a ring does disintegrate the debris does not disperse and seeks to restore its initial state; interactions of several rings produce complex figures resembling spiral and S-shaped galaxies. Not all of them are stable, however, and some plasmic formations are reproduced with great difficulty in subsequent experiments.

The plasmas described in this section belong to the relatively "low-temperature" domain of up to 10,000°C. Between this lower limit and one million degrees there lies a vast unexplored region beyond which plasma studies are now being conducted on a growing scale.

SELF-CONSTRICTING DISCHARGE

The advance of science is frequently compared with the stages of a military campaign, from initial reconnaisance to the final breakthrough and overrunning of the enemy's territory. The front line of scientific advance is real enough, and it passes through laboratories and institutes, pilot plants and experimental installations. A scientific campaign requires of its participants at least as much courage, daring, devotion, and often plain physical strength and grit, as a military campaign does of soldiers.

Continental Antarctica. The coldest place on earth, where the thermometer drops to almost 90 degrees centigrade below zero. Piercing winds the like of which we dwellers of the Temperate Zone have never experienced. There, in plastic buildings at the Pole of Inaccessibility, live the combattants on the front line of science. Wearing electrically heated suits and protective masks, they leave the shelter of their plastic huts to take instrument readings according to a rigid schedule. Who will say that these men are less courageous than scouts crossing enemy lines for vital information?

A spotlessly clean laboratory. Bright sunbeams stream through wide windows. Men in white smocks crowd around a table on which stand test tubes stopped with fluffy balls of cotton. A new serum against a hitherto incurable disease has been prepared. It has passed every test except the crucial one on man. Who will be the first patient to be cured by the new medicine? Many a time it is the discoverer himself who places his life at the service of science, and many a dedicated scientist has sacrificed his life like a soldier on a battlefield.

In science, as in battle, anything can happen. There are protracted sieges of isolated strongholds which nature surrenders only when more powerful weapons—a bigger telescope or better microscope—have been brought into action. There are major breakthroughs, when a new discovery sparks the rapid advance of many fields of science and nature falls back along a broad front. The discovery of the method of "tracer" atoms in physics paved the way for great gains in medicine, metallurgy, geology, botany

and many other sciences. Science also knows of broad outflanking movements when a team of pioneers captures a stronghold deep in the enemy rear. To such a breakthrough belongs the penetration of Soviet scientists into the realm of superhigh temperature plasmas.

The climb up the temperature scale could have followed the same pattern as the way down: gradually, degree by degree, from normal temperature down to absolute zero. It would seem natural that the thousand-degree range of temperatures should be followed by tens and then hundreds of thousands of degrees and up to the million-degree mark. What has actually happened, though, is that the scientists have obtained and are studying temperatures of millions of degrees, leaving the tens and hundreds of thousands of degrees behind. The idea that made possible such a deep flanking movement was advanced by Sakharov, then a young engineer, and Tamm. They designed a receptacle capable of containing plasmas at superhigh temperatures.

Water can be kept in a glass decanter, a wooden barrel or an iron bucket. It would hardly occur to anyone to make a cup out of rock salt. The water in it would always be salty and would ultimately dissolve the sides and bottom and flow out. Different kinds of liquids require different kinds of vessels. Hydrofluoric acid dissolves glass and iron, but it can be kept in a platinum or wax vessel. But platinum would be totally unsuitable for liquid hydrogen, as it absorbs hydrogen. Molten iron is kept in huge ladles lined with refractory brick. What vessel can contain plasma heated to temperatures of tens and hundreds of thousands and millions of degrees? It is not just a question of there being no material capable of remaining solid at the temperatures involved. The important thing is to keep the plasma from coming into contact with the cold walls. For the heat conductivity of plasma is millions of times higher than that of any other material, and it would cool at once. Imagine a wire 100 kilometres long connecting two telephones. If such a wire possessed the heat conductivity of plasma, a fire at one end of the line would within half an hour cause a fire at the other end: if there were no radiation into the

surrounding medium the temperature there would be only slightly less than at the hot end.

Sakharov and Tamm devised a container with "walls" of magnetic field. The first experiment was carried out in the early nineteen-fifties. They took a thick-walled glass tube and filled it with highly rarefied deuterium, an isotope of hydrogen whose nucleus consists of a neutron and a proton (a nucleus of ordinary hydrogen, it will be recalled, consists of a single proton). They attached two electrodes to the ends of the tube, built up a powerful electric charge in a battery of capacitors and applied it to the electrodes. A current of several million amperes, a virtual electrical Niagara, rushed through the deuterium. The power of the current, which lasted for only a few instants, was greater than that of the world's biggest hydroelectric stations.

Such a current generates a powerful electromagnetic field at the surface of the tube. The deuterium turns into a plasma in the manner described before. The electromagnetic field causes the charged particles to gather in a thin column along the centreline of the tube, just as the scientists expected. No charged particle can escape through the magnetic field. The constriction of the plasma is so great that the pressure inside the pinch increases a millionfold. As is known, the temperature of a gas increases with the pressure. If you have ever had to pump a deflated bicycle tire you may have noticed that the bottom of the pump gets warmer. This is not due to the friction of the piston, which is the same along the entire length, but to the compression of air. In the same way the rapid constriction of the pinch makes the temperature jump to a million degrees.

The process, unfortunately, is extremely short-lived, lasting only infinitesimal fractions of a second. The internal pressure of the plasma pinch causes it to expand. When the expansion passes the point of equilibrium between the internal pressure of the plasma and the compressive force of the magnetic field, the plasma collapses again: the column pulsates.

The scientists who first observed the experiment were struck by some strange features. The plasma was quite

unlike the "cold" plasma of several tens of thousands of degrees. It was colourless and almost transparent and did not shine with a blinding light as could have been expected. At moments of maximum constriction the pinch would suddenly spew X-rays and neutrons. Another strange feature was a considerable broadening of the deuterium line in the spectrum during the heating of the plasma.

What is there to prevent scientists from attaining higher temperatures by merely increasing the power of the electric discharge? Unfortunately, there is a major obstacle to this. At high temperatures energy losses by radiation are found to increase much faster than the temperature. The magnetic walls that are impermeable to charged particles are transparent to neutrons, which carry no charge. Most important, they are transparent to visible light, X-rays, radio waves and other types of radiation that carries away energy and brings the temperature down. Maximum temperatures attained so far in Soviet laboratories are in the neighbourhood of 40 million degrees C.

STELLAR FUEL

When, several decades ago, some scientists estimated the known reserves of coal and oil and compared them with the rapid increase in fuel consumption they came to the conclusion that mankind would soon come up against a catastrophic shortage of fuel. They painted a grim picture. First the reserves of oil would be exhausted in not too many years. In their search for the black blood of the earth men would return to old worked beds from which hardly half of the total oil is presently extracted. By employing new methods, such as driving hot steam down wells or electrically heating the beds, they would squeeze out the oil to the last drop. This, however, would not stave off the catastrophe for long. The time would come when automobiles and diesel locomotives would grind to a halt with no fuel in their tanks, aircraft would be grounded, and motorships would rust in their ports.

To be sure, some liquid fuel could be manufactured out of coal, but its reserves would also be exhausted soon. First the best grades of coal would be extracted from more convenient beds, then thin beds that are difficult to work and beds of low-grade coal would be tapped. Water would flood the empty mines. Pieces of coal would be exhibited in museums along with stuffed mammoths and dinosaur skeletons. Steam locomotives would rust on sidings and steam turbines would stop turning. An age of shale, peat and other low-quality fuel would set in. Everything capable of burning would be fed into the fireboxes of engines. Then these reserves would be depleted and the earth would face a calamitous fuel hunger. The civilization based on mineral fuels appeared to be doomed.

Many years have passed since this gloomy prophecy was first made. The forecasts concerning oil ought to have been fulfilled by now and the reserves of coal should be coming to an end. Yet millions of automobiles still fill the roads, airplanes soar in the skies and luxury liners ply the high seas. The extraction of mineral fuels is increasing faster than predicted, but the explored reserves are increasing even faster and the fatal depletion of fuel reserves has been postponed for several centuries and even millennia. Does this mean that the reserves of mineral fuel in the earth are unlimited and the spectre of power destitution is no more dangerous than a fairy-tale ogre? The query includes two different questions which require two separate answers. Firstly, the earth's mineral fuel reserves are not unlimited. The possibility of coal or oil reserves being replenished by natural processes can probably be ruled out and in spite of their vastness, they must surely come to an end one day. Nevertheless man is not threatened with a power shortage. At a certain stage in the development of human society, mineral fuels constituted the main source of power. But just as in the millennia during which man was rising to his feet he got along without coal or oil, so the time will come when neither coal nor oil will be important power sources any longer. The primary source of power in the forseeable future will most likely be the atomic nucleus.

Why is nuclear power ranked above the energy of the wind and tides, the thermal energy deep in the earth or the unlimited energy of the sun?

The power output per square metre of the rotor of a wind-driven generator can reach 6.7 kilowatts with a wind speed of 12 m/sec.

A solar electric station can yield a maximum of 1 kilowatt per square metre.

The calorific value of one kilogram of hard coal is 7,000-8,000 kilocalories.

The calorific value of one kilogram of oil is 11,000 kilocalories.

In comparison, one kilogram of uranium, already a widely used nuclear fuel, can yield 22,300,000 kilowatt-hours of energy. An even better nuclear fuel is hydrogen, with an energy potential of 117,500,000 kilowatt-hours per kilogram.

In the presence of one of the authors of this book Academician Lev Artsimovich drew a sketch of what a thermonuclear electric station of the future might look like and jotted down several estimates. The power plant of a one-million-kilowatt station of this kind could be housed in a circular one-storey building 12 metres in diameter. The power output per cubic metre of "working volume" could reach 200,000 kilowatts. One need hardly compare this with the huge boiler and turbine houses of modern electric stations nor with the mile-long dams and ten-storey high turbine-generator units of hydraulic power plants.

The world's first atom-powered electric station has been in operation in the Soviet Union since 1954. In 1958, the first section (100,000 kW) of a 600,000-kW atomic electric station was commissioned. Today big atomic electric stations are in operation and under construction in many parts of the Soviet Union as well as in other countries. The future, however, does not belong to this type of power plant, although it will undoubtedly play an important part in world power production for some time to come. In the 21st century power production will be based largely on thermonuclear plant.

The reserves of uranium and thorium, the fuel of modern atomic electric stations, though substantial, are not unlim-

ited. The stocks of hydrogen on earth and in the universe are virtually inexhaustible. For every molecule of water contains two atoms of hydrogen, and water covers 70 per cent of the earth's surface. True, Sakharov's and Tamm's plasma pinch described in the previous section consisted not of hydrogen but of deuterium. But this isotope of hydrogen is not so rare as one might imagine: on earth it occurs in the ratio of one atom per every 6,000 atoms of "ordinary hydrogen". The ratio holds for water, and to every 6,000 molecules of common water there is one molecule of "heavy water", D_2O. The deuterium energy content in one gallon of water is equivalent to 400 gallons of oil.

Heavy water is still very expensive, but it is used industrially in "conventional" nuclear power plants, in the production of nuclear fuels and in other processes. When man learns to use deuterium as a nuclear fuel the power produced by it will be cheaper than power production by thermal or hydraulic electric stations. It is estimated that in time the cost of a kilowatt-hour of thermonuclear electricity will be only one per cent of that of thermal electricity.

The principle of thermonuclear power production is extremely simple. Hydrogen has three isotopes: common hydrogen (protium), whose nucleus consists of a single proton; deuterium, whose nucleus consists of a neutron and a proton; and tritium, with two neutrons and a proton. The fusion of two deuterium nuclei, or a tritium and a protium nucleus, or a deuterium and tritium nucleus (other combinations are also possible) yields a helium nucleus and a great amount of energy. But can two atoms of deuterium be made to fuse?

Suppose we have a fantastic superhigh-power microscope in which we can observe elementary particles. In the eyepiece we see molecules of gas rushing helter-skelter, colliding and rebounding like little rubber balls. We increase the magnification and raise the temperature by heating the object glass with a "match" capable of producing a flame ranging in temperature from several hundred degrees to several thousands of millions of degrees. We observe that racing among the relatively slow-moving

molecules are some free electrons. One of them hits a molecule, which splits into two ions with the emission of several more electrons. As we raise the temperature of our "match" the collisions become more and more frequent. The number of electrically neutral molecules rapidly decreases and more and more fast-moving ions and electrons appear until there are no molecules left at all.

A careful inspection reveals that no matter how fast the hydrogen, deuterium and tritium nuclei move they do not collide. They skillfully manoeuvre and make way for each other. This kind of behaviour is easily explained, for atomic nuclei consist of positively charged protons and chargeless neutrons. But like charges repel each other, and it is these repelling forces that do not let the nuclei collide. Each nucleus is surrounded by an invisible but very real shell of electrical field. These shells react on contact and make the nuclei rebound.

Let us raise the temperature still higher in the hope that a chance collision might occur in the growing chaos of jostling nuclei. Sure enough, here are two nuclei racing head on. Their momentum is so great that the impact deforms the electrical field shells and the nuclei come quite close to one another. One could expect the electrical forces of repulsion to recoil like a tight spring and hurl the nuclei apart. But all of a sudden the two nuclei rush towards one another and fuse into a single new nucleus much as two drops of mercury join into a bigger drop. This means that nuclear forces have come into play. The fusion is like an explosion. Quanta of waves of different kind are splashed in all directions and the newly formed nucleus of helium acquires a tremendous velocity.

As the temperature of the plasma rises collisions between nuclei become more frequent and the energy output of the thermonuclear reaction correspondingly increases. The moment finally comes when the energy output of the reaction itself begins to contribute to the plasma's temperature and the number of collisions rises steeply. Hadn't we better get away from our microscope in case a hydrogen explosion takes place? Indeed we should. Above a certain temperature the deuterium plasma begins to yield an

avalanche of energy. This is the principle on which the hydrogen bomb is based.

Several designs of thermonuclear power plant have been suggested. In one the plasma tube is bent into a doughnut—mathematicians call it a torus. Such an installation need not be more than about 10 metres in diameter, with the containing tube only one metre thick. Around the doughnut are arranged pumps for evacuating the tube, current collectors and other power station equipment. Inside the tube the thermonuclear fuel—a mixture of deuterium and tritium—is compressed by a magnetic field. Several coils of wire are wound around the torus: one for creating the "magnetic bottle", one for controlling the plasma column, and one for generating the electric current.

You will observe that the setup disposes not only of steam boilers and turbines, but also of electric generators. Indeed, a thermonuclear power plant does not need a special generator. Plasma, it will be remembered, is a good conductor of electricity and it produces an electromagnetic field. Fluctuations in the plasma column cause fluctuations in the electric current, and hence in the electromagnetic field. And a variable magnetic field induces electric current in a conductor crossing it. In other words, a thermonuclear power plant does not need turbines, generators and other conventional power plant, which, however, could be installed as auxiliary equipment. As mentioned before, plasma radiates large quantities of energy. The torus walls would naturally be very hot and would have to be cooled with water. The steam from this water could be used in the auxiliary departments of the thermonuclear power plant.

It was a sketch of this kind of plant that Professor Artsimovich had drawn in his notebook. He also pointed out the difficulties in realizing such a project. The main obstacle to date is the development of a "bottle" capable of containing the plasma for a sufficiently long time without cooling. Two types of plasma traps are currently being considered.

One we have just spoken of, namely, a hollow tube bent into a huge doughnut and filled with deuterium gas.

An external electric charge ionizes the gas and produces a ring of plasma. The current passing through the plasma heats it and at the same time creates a magnetic field which keeps it from touching the walls. Wire coils wrapped around the torus create an additional magnetic field which "heals" the plasma of its inherent instability. It is still too early to say whether this method can ensure the necessary isolation of the plasma.

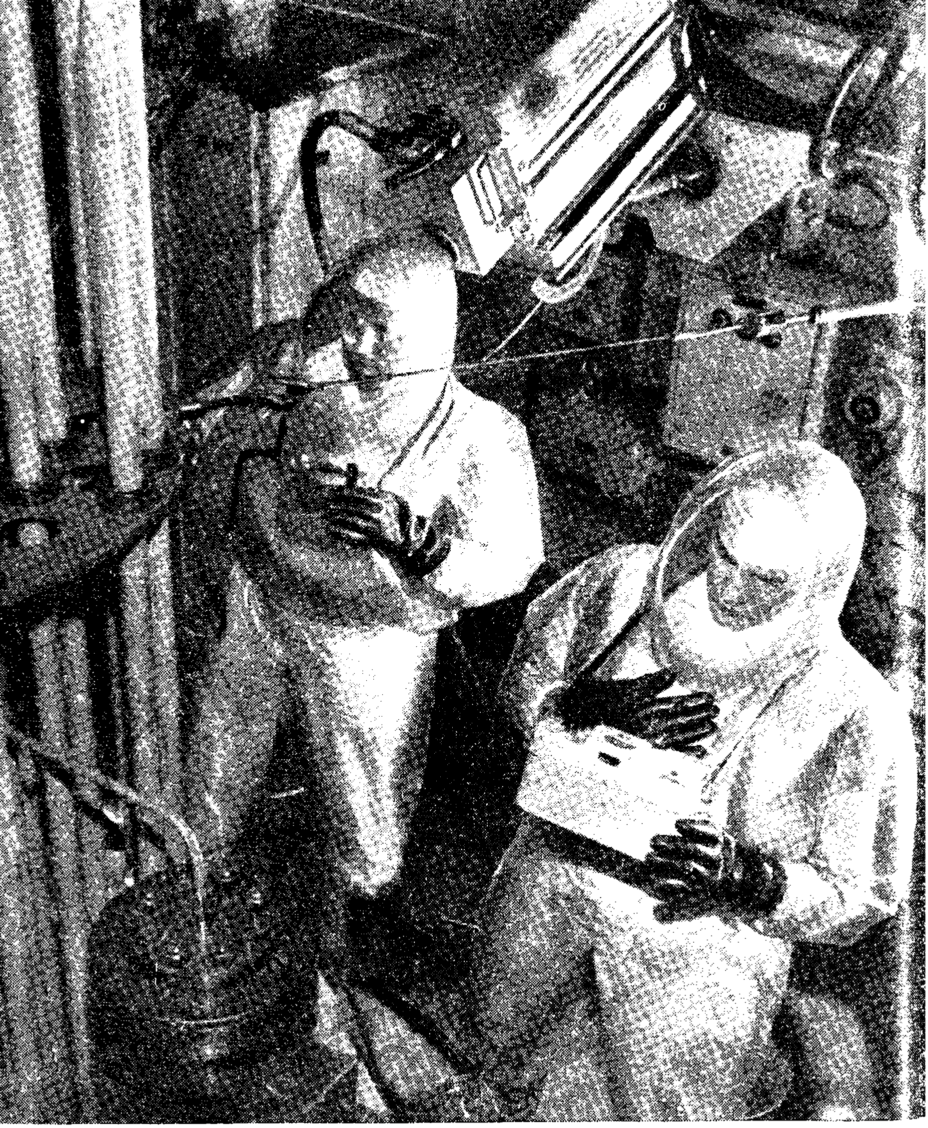
Another method has been suggested by the Soviet scientist G. Budker. There is no need to bend Sakharov's and Tamm's tube into a doughnut, he reasoned. Instead, one could stop the ends with magnetic mirrors. Mathematical computations confirmed that in certain conditions the plasma particles within such a tube—it is called an adiabatic trap—would travel back and forth, bouncing away from the magnetic mirrors like steel balls from a marble floor. The Soviet thermonuclear installation *Ogra* is based on this adiabatic trap principle. This method, too, does not ensure complete insulation, and ionized particles escape and dissipate energy. Scientists have computed and plotted curves for the energy losses through the "plugs" of the adiabatic trap and the dependence of energy output on temperature. We know that the higher the temperature the greater the number of nuclear collisions and the higher the energy output. It has also been found that the higher the temperature the less the energy losses of the plasma in the trap. The intersection of these two curves on a graph gives the temperature at which thermal equilibrium sets in and the dissipation of heat by the plasma is exactly balanced by the heat input due to the reaction of synthesis of helium nuclei. The equilibrium temperature for deuterium-tritium fusion was found to be about 1,000 million degrees C. For deuterium-deuterium synthesis the optimum temperature is about 10,000 million degrees.

These figures offer an idea of the distance that is yet to be covered before thermonuclear power plants can ever be built. On the other hand, never has science advanced so rapidly as in our time. Temperatures of hundreds of millions and then thousands of millions of degrees may be achieved by a gradual climb up the temperature scale,

through the perfection of thermonuclear toruses and adiabatic traps, although the obstacles along this road are formidable. A more likely development, however, would be a new "outflanking" manoeuvre as a result of which the scientists would invade the thousand-million degree temperature domain, leaving behind the "blank spot" of hundreds of millions of degrees.

Astrophysicists say that the energy which feeds the eternal fires of the sun is thermonuclear energy. All the more wonderful the exploit of the Prometheuses who will steal that stellar fire and kindle it on earth.

Field



Dosimetrists at work on board the nuclear-powered icebreaker "Lenin"

INTANGIBLE MATTER

In his story, *The Country of the Blind*, H. G. Wells describes the experiences of a man who finds himself in a land-locked valley hemmed in by impassable mountains where all the inhabitants are blind from birth. Even their legends carry no reference to ancestors who could see. Leaving aside the philosophical idea of the story, in which the blind people of the valley symbolize the whole of mankind, let us try and answer the question: could a sightless man gain an adequate knowledge of the world with only the senses of smell, taste, touch and hearing? And, especially, could he learn anything about light and colour?

The answer is undoubtedly yes. Cognition would surely be a much more tortuous and slower enterprise, insofar man gains some 80 per cent of his information about the outside world through his eyes. But his powers of cognition are truly boundless. A blind race of men

would be well aware of solar radiation due to the warmth it carries. With the help of a few simple instruments and a thermometer a blind scientist would discover the laws of refraction of light. His thermometer could be made of a bimetallic strip: it would show the temperature by the degree of its deflection, which the man could easily ascertain by touch.

Blind scientists would discover the spectrum of sunlight. True, they would not observe the boundary between the "visible" portion and the ultraviolet and infrared. Later on, by observing the tides and using highly sensitive thermocouples, they could discover the existence of the moon and stars and single out the planets from the latter. The instrument readings would be in terms of sounds, smells or tangible changes of state. Obviously, a blind humanity would never describe the things we perceive as the red of blood or the green of grass. But a blind physicist in an advanced civilization could say: "Red light represents electromagnetic oscillations with a wavelength of 0.75 micron, green light has a wavelength of about 0.55 micron, and violet, 0.4 micron." And this is essentially what any other physicist would say.

On the other extreme, we can easily imagine a creature capable of vision not only in the portion of the spectrum which we can see but in the whole of the electromagnetic spectrum, from radio waves to X-rays. To such a creature the antennas of radio transmitters would be like brilliant lights, trolley wires and electrical mains would glow, and warm human bodies and central heating radiators would emit a halo of radiation. And he would consider us to be as blind as bats. Nevertheless, we could probably tell him: "To be sure, we do not know what electromagnetic radiation with a wavelength of 6 metres 3 centimetres looks like to you. But we do know the laws it obeys and we have put it to work even though we can't perceive it with any of our natural senses. The local T. V. centre, for example, broadcasts on this wavelength. In fact, we have a fair knowledge of the whole of the electromagnetic spectrum."

Take a glass prism and let a ray of light pass through it. The light breaks down into its component colours.

It is very hard to point to the exact place where the red end of the spectrum ends finally becomes invisible. More, there is no need for this. Beyond it extends a region of infrared radiation which is several times bigger than the visible portion. It is followed by radio waves, starting with portions which as yet find no scientific or technical applications. The offensive against them has begun, and when they are finally mastered one of the dreams of science fiction writers will come true and every man will be able to have a "walkie-talkie" of his own with his own private wavelength.

Then come the ultrahigh frequency (UHF) wave bands which are currently being widely developed. This is the region of television and interference-free sound broadcasting. It is followed by the well-known and widely used short-, medium-, and long-wave radio bands. An expert will not hesitate to suggest the best wavelength for communication with a spaceship heading for Mars or between two radio stations halfway around the earth. He knows how to calculate and build generators of these waves and extremely sensitive receivers for them.

At the other end of the visible spectrum, the dark-violet region is followed by the shorter-wave ultraviolet, which passes gradually into the X-ray band (in fact, there are no sharp boundaries along the whole of the spectrum). Man, of course, has learned to make use of the penetrating ability of X-rays. They are followed by the even more penetrating gamma radiation, which takes a twenty-centimetre layer of aluminium to reduce its intensity by one-half. One of the main sources of gamma radiation are nuclear processes.

The difference between various portions of the electromagnetic spectrum is striking indeed. How unlike visible light, which is incapable of piercing a delicate sheet of metal foil and bends so easily in passing from one medium into another, is the penetrating force of gamma radiation. Yet in vacuum all electromagnetic waves, irrespective of their origin and the portion of the spectrum to which they belong, are similar and obey the same laws, for they are all products of electromagnetic field emission. The differences between them are a natural consequence of

the accumulation of quantitative differences. Moving along the electromagnetic spectrum, we can trace how the accumulation of quantitative changes results in qualitative changes.

Electromagnetic waves are inseparable from electromagnetic fields. An electromagnetic field is generated by flowing electricity. When current passes through a conductor an electromagnetic field immediately appears around it. To be more precise, it appears not quite at once: in vacuum it propagates with the tremendous but finite velocity of 300,000 kilometres per second. Changes in the electric current alter the field. Thus, the pulsation of electricity in the antenna of a transmitter produces an electromagnetic field which spreads in all directions. The field meets the antenna of a receiver and induces an electric current in it. Millions of times weaker than in the transmitting antenna, to be sure, but the fluctuations follow the same pattern, and in the wireless we hear the very melody which is still echoing in the radio studio.

Often we are annoyed by the crackle and whistling of static and other interferences. They are due to "wild" radio waves that are originated by natural causes. Where do they appear? Where has nature spread its antennas and mounted its electron tubes? Nature has no need for them, and radio waves are produced in the destructive discharge of a bolt of lightning, in the noiseless shimmer of the aurora borealis and in the collisions of electrons in distant clouds of cosmic gas. All these are processes which take place in plasma, and although man is blind to the radio wave spectrum he has learned to see them with the help of ingenious instruments.

An important property of electromagnetic field is its dual nature. The question, "What is an electromagnetic field?" was preceded by the question, "What is light?".

Some scientists said that light represented streams of tiny particles or corpuscles. Others declared that light represented waves carried by the "luminiferous ether" (a medium whose existence was postulated for that sole purpose of explaining the propagation of light), and they cited refraction, diffraction and other phenomena in support of their theories. As happens very rarely in sci-

ence, both parties in the controversy proved to be right. Many indubitable, scientifically verified observations testify to the fact that light, electromagnetic radiation and fields are of a dual nature. Light can be treated as a flux of photons of different energies and as a train of electromagnetic waves of different lengths or frequencies. The longer the wave the harder it is to observe particle properties in its behaviour and, conversely, the shorter the wave the less manifest its wave properties. Gamma rays display hardly any wave properties, which is why they are also called gamma particles. The important thing to be borne in mind is that radio waves, light rays and gamma particles are all essentially of the same nature and represent different types of electromagnetic field.

The tiny particles of light are called photons; the particles of electromagnetic field in general are called quanta. They are the elementary particles of electromagnetic field just as electrons, protons and neutrons are the elementary particles of matter. The quantized structure of fields has been proved experimentally, and it is as indubitable as the existence of electrons.

Is electromagnetic field a material entity? Undoubtedly. It reacts with matter. It carries energy. It has mass. A substance that generates an electromagnetic field expends a part of its mass and energy in the process. True, the quantitative relationships are such that it is impos-

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Mathematically speaking

FIELD PRESSURE

The density of matter in interstellar space is no greater than 10^{-24} g/cm^3, which corresponds to one atom of hydrogen per cubic centimetre. But outer space is pervaded with fields of different kinds: electromagnetic (in particular, light) and gravitational. From the relativity theory, these fields are ponderable, in other words, they possess mass.

Light, like any other field, exerts pulsed pressure, a fact which was first established theoretically in the 19th century (before the enunciation of the relativity theory) by James Clerk Maxwell and experimentally verified in 1901 by the Russian physicist P.N. Lebedev. The pressure of a light pulse, P, is given by the expression

$$P = \frac{E}{c}$$

where E is the energy and

sible to measure the reduction in mass of, say, a white-hot ingot radiating light in all directions. But the decrease in the mass of the sun due to radiation and the continuous generation of a surrounding electromagnetic field covering the whole spectrum from radio waves to gamma rays is pretty substantial. The sun loses thousands of millions of tons of matter daily. We have nothing to fear, however, and at the present rate of expenditure the sun will last for many thousands of millions of years. In certain conditions the reverse transformation is possible, and field may change into matter.

Electromagnetic waves of all lengths find a great many applications in industry. And although we still have much to learn about the electromagnetic spectrum and many new applications of various parts of it are still to be devised, it is the best known and least mysterious of the fields. Incidentally, the field surrounding an ordinary magnet is a special case of electromagnetic field.

Much less is known of gravitational and nuclear fields, which are largely unexplored domains still awaiting their Columbuses. Let us see what is known about them. First, fields of gravity.

OMNIPRESENT FORCE

There is no escape from gravity. Its eternal laws are valid in the remotest parts of the universe, it equally pervades vacuum and the densest substances, there is no way of shielding from it or acting on it. It decreases with dis-

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$c=300{,}000$ km/sec is the speed of light.

The energy of light is connected with its frequency and wavelength by the expression

$$E = h\nu = \frac{hc}{\lambda},$$

where $h=6\times 62\times 10^{-27}$ erg.sec is Planck's constant, ν is the vibration frequency, and λ is the wavelength. Substituting this formula into the previous one, we have

$$P = \frac{h}{\lambda}$$

that is, the pressure of light varies inversely as its wavelength.

The pressure of light

$$P = \frac{\omega}{c}(1+R)\ \text{erg/cm}^3$$

where ω is the energy of radiation vertically incident on cm^2 per sec.

tance, but never disappears completely. Hence the law of universal gravitation. Gravity makes rivers flow down to the sea and keeps the atmosphere around the earth. It takes a velocity of no less than 8 kilometres per second to place an artificial satellite in orbit, 11.2 kilometres per second to escape the earth and leave it for good, and 16.7 kilometres per second to overcome the gravitational pull of the sun.

Since time immemorial man has had to reckon with gravity, and he has learned to adapt it to his own needs. Truly the oldest known force, it remained unexplained for ages. The first man to develop a scientific theory of gravity and apply it to the study of the universe was the great Englishman, Sir Isaac Newton.

The anecdote that Newton discovered his law of universal gravitation by watching an apple fall from a tree may be true or not. It has been said that he invented it himself to get rid of people demanding an explanation of just how he had discovered the great law. Today any high-school student can rattle off the law with such ease that it seems strange indeed that there was a time when learned men had not the slightest idea about it. However, it is not so simple as it may appear to us and it took the genius of Newton to discover it.

The law of universal gravitation states that every two material bodies attract each other with a force that is proportional directly to the product of their masses, and inversely as the square of the distance between them. Newton applied the law to the most diverse phenomena and boldly extended it to the whole of the known universe. It proved to be equally valid at the surface of the earth and on a universal scale.

Sixty or seventy years before Newton's time, the great German scientist Johannes Kepler discovered the basic laws governing the motion of the planets around the sun These laws, too, are familiar to the high-school student of today, but in Kepler's time they did not have a firm basis. To be sure, the planets moved according to Kepler's laws, but no one could explain why. It was left to Newton to prove that their motions are governed by the law of gravitation, and he used it to develop Kepler's formulas.

The law of universal gravitation found brilliant confirmation in the discovery of the planet Neptune. Astronomers had long observed that the planet Uranus occasionally appeared to stray from its orbit as predicted by the laws of gravitation. It would inexplicably slow down its motion among the stars, or again it would go faster, as if drawn by some invisible force. Pondering over this phenomenon, the Russian astronomer Leksell, at the end of the 18th century, came to the conclusion that an unknown planet beyond Uranus must be responsible for it. In 1846, the French mathematician Leverrier calculated the position of the new planet in the sky, and soon the astronomers discovered it. This was a great triumph of science.

For many decades Newton's classical theory of gravitation appeared to be infallible. Then facts began to accumulate which could not be explained by the law of gravitation alone. One of these is the so-called Seeliger paradox, which consists in the following. The universe is infinite and infinitely variable. Its lifetime, too, is unlimited. It is more or less filled with material bodies, which is to say that the universe as a whole possesses some mean density of matter. Seeliger decided to apply Newton's law and determine the gravitational force which an infinite universe would exert at any point within it. The force, he found, was proportional to the radius of the universe. But if the universe is infinite it follows that the

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Mathematically speaking

NEWTON'S AND COULOMB'S LAWS

As Newton showed, between two bodies there acts a gravitational force, F, which varies directly as the product of their masses, M_1M_2, and inversely as the square of the distance, r, between them. Newton's law of gravitation is expressed by the formula

$$F = G\frac{M_1M_2}{r^2}$$

where G is the so-called gravitational constant. In the CGS system of measurement (CGS stands for centimetre-gram-second) $G=6.67\times10^{-8}$ cm^3 g^{-1} sec^{-2}. This value was determined empirically.

The quantity

$$\frac{F}{M_2} = g = \frac{GM_1}{r^2}$$

force of gravity at any point must also be infinite. This, of course, is not the case. But does it mean that the law of gravitation is not valid on the universal scale?

Many hypotheses were advanced to explain this paradox. One of the first postulated that the density of matter in the universe decreases with distance. This means that if we go sufficiently far out we can come to a region devoid of matter. To suggest this means to suggest that space can exist without matter, which is absurd, for space can be envisaged only as a form of existence of matter. Seeliger himself offered a different explanation. He assumed that the force of gravity diminishes, not as the inverse square of the distance, but faster. This partially explained the paradox, but it cast doubt on the validity of Newton's classical law.

Another phenomenon in which the conclusions of gravitational theory did not quite agree with observations was found in the precession of the perihelion of Mercury. Very accurate calculations of elliptical planetary orbits reveal that their perihelions (the points closest to the sun) must suffer a precession, or displacement, in the direction of the planet's rotation. For Mercury the calculated precession should have been 5,558 angular seconds in 100 years. Astronomical observations, however, revealed

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yields the acceleration of a body of any mass M_2 subjected to the gravitational attraction of a body of mass M_1.

Analogous in form is Coulomb's law, which states that two charged particles are attracted (if the charges are opposite) or repulsed (if they are the same) with a force, f, which varies directly as the product of the charges and inversely as the square of the distance between them:

$$f = A\,\frac{e_1 e_2}{r^2}$$

where e_1 and e_2 are the respective charges, and A is a coefficient of proportionality. If, in the CGS system, the charge of an electron, $e = 4.8 \times 10^{-10} g^{1/2}\,cm^{3/2}\,sec^{-1}$, is taken for the unit charge, then

$$f = \frac{e_1 e_2}{r^2}$$

From the foregoing formulas the important conclusion can be drawn that in the subatomic domain the effects of gravitational forces are vanishingly small as compared with electrostatic forces.

a precession of 5,600 angular seconds. For a long time the extra 42″ remained an inexplicable freak of nature. It took a revolution in science to explain it, and this revolution was carried out by the great German scientist, Albert Einstein.

DR. EINSTEIN'S REVOLUTION

That sound travels with finite, and not very great, velocity, was known very long ago. If a gun fires at a distance you will see the flash of light some time before you hear the report. It is thus possible to measure the speed with which sound propagates, which in the air at the surface of the earth is about 330 metres per second. It is much harder to determine the velocity of light which, as we know today, has the incredible value of almost 300,000 kilometres per second. A ray of light could circle the earth in just over 0.1 second, and for a long time people were unable to measure its speed. This was finally achieved by observing the eclipses of the satellites of Jupiter from two points on the earth's orbit around the sun, when the earth was closest to and farthest from Jupiter. The time of the eclipse was calculated to an accuracy of fractions of a second, but the observed times were found to differ by several minutes. This, it was concluded, was due to the additional distance which light from the satellite had to travel along the diameter of the earth's orbit. This distance being known, the scientists were able to calculate for the first time the velocity of light. Today it is measured in laboratory conditions to a high degree of accuracy by means of rotating mirrors. The speed of light is the velocity with which electromagnetic fields propagate through space.

How fast does a gravitational field travel? As fast as sound in air, light in vacuum, or with some other speed? It was once assumed that bodies attracted each other directly, without the participation of the intervening medium. Materialistic thinking, however, cannot accept the concept of interaction at a distance, "through nothing". Science tells us that a physical process can be transmitted only directly from one body to another. There

must inevitably exist a reciprocal sequence of cause and event in both space and time. A bullet hits a target after it has been shot out of a barrel. The report of the shot can be heard after the shot occurred, etc. It follows from the concept of consecutive propagation that gravitational forces and gravitational fields do not propagate instantaneously. They must have a finite velocity, presumably equal to the speed of light. A new theory was needed to take this into account. Its foundations were laid in 1905-1915 by Albert Einstein in his special and general theories of relativity. In his work he proceeded from the geometries of Lobachevsky and Riemann.

One of the fundamental conclusions of the special theory of relativity, which defines the interconnections between space and time, is the equivalence of mass and energy. A moving body, the theory states, carries kinetic energy, hence its mass is greater than when it is at rest. The greater a body's latent energy the greater its mass, and a cup of hot coffee is heavier than the same cup of cold coffee. From Einstein's formula of mass-energy equivalence it follows that a kilogram of mass corresponds to the incredible energy of 9.18×10^{15} kilogram-metres.

But what is meant by a body's mass? The mechanical concept of mass states that mass is the measure of a body's inertia. Hence, mass can be expressed in terms of force and the acceleration which it imparts to the body. In physics mass measured in this way is known as inertial mass. But mass can also be determined from Newton's formula of gravitation. This mass of bodies which may be at rest relative to one another is known as gravitational mass. The physical interpretation of inertial and gravitational mass is different, but quantitatively they have to date been found to be the same for the same body no matter how they are measured. We have just said that a body's inertial mass varies with the velocity of motion. Hence, Einstein reasoned, the gravitational mass should also change with the velocity. The conclusion he drew from this was that inertia and gravity forces must be of a common origin.

The equality of the propagation speed of electromagnetic waves and light led James Maxwell to postulate that

light was a form of electromagnetic radiation. He brought electromagnetic waves and light together in the electromagnetic spectrum discussed before. His hypothesis proved to be correct and it contributed substantially to the progress of science. Of like significance was Einstein's identification of inertia and gravity on the basis of the equality of inertial and gravitational mass. It enabled him to develop in 1915 the general theory of relativity—the modern theory of gravitation, which offers a much more exact and profound interpretation of the properties of the bodies than Newton's theory. Einstein's theory was a revolution in physics which provided an explanation for many hitherto inexplicable phenomena. It would hardly be useful to present here the general theory of relativity, the exposition of which is largely mathematical and the formal aspect of which is extremely involved in spite of the clarity of its physical meaning.

Many corollaries of general relativity have been brilliantly confirmed in scientific experiments and observations. Thus, according to the theory, a ray of light passing through a powerful gravitational field should bend, just as the path of a stone thrown parallel to the earth is deflected by the latter's gravity. For the ray of light, like the stone, possesses mass. To be sure, its mass is very small and the velocity is very great, which requires a very strong field indeed to make its deflection observable.

Mathematically speaking

EINSTEIN'S THEORY OF GRAVITATION

Einstein's theory of gravitation is presented in his general theory of relativity. When we act on a body of mass m with a force F the body receives an acceleration, which we can denote g, such that $F=mg$. If the body receives the same acceleration in a gravitational field we conclude that it is subjected to the same force $F=mg$. In the former case one deals with the body's inertial mass (in the sense that one must apply a force to overcome the body's inertia), in the latter case one deals with its gravitational mass (in the sense that in a gravitational field all bodies receive the same acceleration). One thus finds that the inertial mass equals the gravitational mass. This is an important principle of the relativi-

Such a field is provided by the sun, and it was used to verify the "Einstein effect". During an eclipse of the sun on May 29, 1919, astronomers photographed the stars next to its disk. The same portion of the sky was photographed half a year later, when the sun was far away. When the photographs were superimposed the positions of some stars failed to coincide. This was due to the sun's gravitational attraction, which bent the rays passing by it thus shifting the apparent positions of the stars. The value of the deflection, observed eight times between 1919 and 1952 to accuracies of up to 12 per cent, tallies well with the predicted value (for a ray grazing the edge of the sun's disk the predicted deflection is $1''.75$; the observed deflections vary from $1''.61$ to $1''.98$). The general theory of relativity also provided an explanation for the "misbehaviour" of Mercury's perihelion from the point of view of classical celestial mechanics.

The question now is, can general relativity be applied to the whole of the infinite universe? The equations of general relativity are extremely complicated, belonging as they do to the class of so-called nonlinear differential equations, which do not yield exact solutions for arbitrary initial conditions. Figuratively speaking, scientists have in their hands a sharpshooter's rifle capable of hitting

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ty theory, the principle of the equivalence of gravitational and inertial mass.

Even before the enunciation of the relativity theory an interesting calculation was carried out. Assuming that light is also attracted by celestial bodies, the sun, for instance, one can compute the path of a light beam grazing the sun. In these computations the laws of Newtonian mechanics and gravitation were applied to an imaginary body travelling in the sun's gravitational field at the velocity of light, c. The calculations yielded that for a terrestrial observer the deflection of a ray of light from a distant star grazing the sun should amount to $0''.83=0''.85$. But photograps taken during eclipses of the sun yield a deflection of about $1''.75$, almost twice the theoretical value. This discrepancy is explained by the relativity theory.

According to this theory, matter deforms and warps the space around it. The greater the density of matter in a given region the greater the space curvature. The motion of bodies along

the bull's eye, but they are unskilled in manipulating the sights. Before they can solve and use the equations they must either simplify them or assume simplified initial conditions. That was how Einstein used them to investigate the general properties of the universe.

Continuing the comparison, we could say that being unable to make use of the rifle sights the "sharpshooters" had them removed and took aim by peering through the barrel. The simplifications involve terms of the second and third order and the resulting error is therefore not too great. Thus, the basic equations take into account the interaction of the electromagnetic field produced by a ray of light with the gravitational fields of the bodies near which it passes, as well as the effects of gravitational fields on themselves. The simplified equations do not take these interactions into account as in terrestrial conditions and in spatial domains compatible with the size of the earth, or even the diameter of the earth's orbit, their effects are negligible. But over the vast distances which light spans the energy of interaction is commensurate with the energy of the light flux and must accordingly differ markedly from the values given by the approximate solutions.

To sum up, as far as contemporary mathematical knowledge allows of its application, Einstein's theory of gravitation is much more exact than Newton's classical

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curved paths produces gravitational phenomena, just as a train's motion along a curve produces inertial centrifugal forces.

In a curved space the shortest distance between two points is not a straight line, just as on the surface of a sphere the shortest distance between two points is an arc of a great circle (a great circle, or geodetic, is the line of intersection of a spherical surface with a plane passing through its geometrical centre). The mathematical description of motion in such paths is extremely involved and no simple relationships can be offered. Gravitational forces are found to depend not only on the curvature of space, but also on the velocity of bodies.

Gravity affects light not only by deflecting it but also by changing its wavelength. In a beam of light travelling from a massive body the wavelength, λ, increases (it appears redder); in a beam of light travelling towards a massive body the

theory. It can be used to study much larger spatial domains, though it cannot be applied to the whole of the infinite universe. Its advantage over Newton's theory is that it can be applied without any correction factors to explain such phenomena as Seeliger's paradox and to study the universe at immeasurably greater distances.

THE EXPANDING UNIVERSE

One of the solutions of the basic equations of general relativity developed by the Soviet scientist A. A. Friedman leads to the conclusion that the universe is steadily expanding. From this it was concluded that the density of matter in the universe is steadily decreasing and the distances between galaxies are increasing. The hypothesis of "fleeing galaxies" and the "expanding universe" could be verified by measuring the apparent velocities of observable galaxies. This is undoubtedly easier said than done, but the astronomers found a way out. Their method is based on what is known as the Doppler effect. If you have ever been on a railway platform when a train passes without stopping, you may have observed that as it approaches the pitch of its whistle rises steadily to a shriek. A meas-

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wavelength decreases (it appears bluer). This phenomenon is described by the simple equation:

$$\frac{\Delta\lambda}{\lambda} = \pm \frac{mG}{rc^2}$$

where $\Delta\lambda$ is the shift in wavelength, r is the distance to the body, and m is its mass. The effect is perceptible and can be observed in heavy stars. For the sun

$$\frac{\Delta\lambda}{\lambda} = 2 \times 10^{-6}$$

Another effect of general relativity—the displacement of the perihelion of bodies travelling in elliptical orbits—is mentioned in the text.

With a view to the possibility of absorption of gravitational energy and the creation of particle pairs, the law of gravitation for a weak field can be written in the form

$$F = \frac{Gm_1m_2}{r^2} e^{-\frac{r}{R}}$$

where R is the distance of free motion of a graviton (the distance it can travel without being absorbed), which is of the order of 10^{27} to 10^{30} cm, and $e=2.72...$ is the base of natural logarithms.

urement of the rate of change in the pitch of the whistle would provide a measure of the speed with which the train is approaching the station. The same principle is used to measure the velocity of distant galaxies. Only instead of a change in the frequency of sound vibrations the change in the frequency of electromagnetic vibrations is measured. It is observed as a shift in the spectral lines of elements in the light spectra of the galaxies. When the velocities of a score of close and distant galaxies were measured the spectral lines were found to be displaced towards the red end of the spectrum—the so-called red shift—indicating that the galaxies were in fact moving away from us. The scientists also found that the farther a galaxy the greater its velocity appears to be. The red shift offers convincing proof that the galaxies are in fact "fleeing", the remotest observable ones at velocities of 60,000 kilometres and more per second.

But if the galaxies are at present flying apart, it stands to reason that there must have been a time when they were much closer. Astronomers' estimates indicate that several thousands of millions of years ago all the galaxies must have been concentrated in a small space of our part of the universe. Scientists of another speciality, geophysics, undertook to establish the age of terrestrial rock and meteorites, the only cosmic bodies available to us for direct investigation by the method of radioactive dating. Their findings indicate that the matter of the earth and meteorites was formed some 5,000-6,000 million years ago, which tallies well with the astronomers' calculations.

These findings served as the basis for a hypothesis according to which all the matter of the observable universe was once concentrated in a "primeval egg". When it exploded the debris began to scatter at a tremendous speed. Galaxies, nebulae and other celestial bodies formed in the expanding products of the explosion, and out of them there appeared stars and planetary systems. According to this theory the whole of the universe is confined to the region of the explosion.

The latter conclusion, in our view, is hardly tenable. Undoubtedly, the universe appears to be expanding. The facts are there, and the red shift is clear indication that

the galaxies are "fleeing" while "uranium clock" readings indicate the time when the substances of which the earth and meteorites are composed came into existence.

Consider the following model. Suppose at some initial time the particles of a gas begin to collapse towards the centre of their volume. When they come together the system will be at rest, with a tremendous store of kinetic energy of the particles. The release of this energy starts pushing the particles apart. A shock wave travels from the centre to the periphery of the sphere, and expansion begins. The particles at the perimeter of the sphere shoot away faster than the deeper particles. This is demonstrated by a very simple experiment. Place several checkers in a row so that each one touches its neighbour and strike a sharp blow with a ruler at one end. The impulse will travel through all the checkers and the one at the other end will slide away. The penultimate checker will move only slightly and the others will remain practically in their places. Now if the particles of the expanding gas mutually attract one another a time will come when the interior particles will start falling back to the centre. This collapse will be followed by a new expansion and so on ad infinitum: the nucleus will pulsate. We have observed something like this in the pulsation of a plasma column.

Expanding our model to the scale of the universe, we can imagine that there was a time when all the matter of the universe was collapsing under gravity towards its geometrical centre. The resulting superhigh pressures could trigger nuclear reactions of different kinds producing a tremendous explosion in which gigantic puffs of matter flew out in all directions. We may well be witnessing the results of this cataclysmic explosion. The time when it took place is given by the "uranium clock". Obviously, we can only conjecture as to the nature of the explosion. We have no way of knowing the forms matter took before and during the explosion: although matter is eternal, its forms may vary and change endlessly. One thing which we can say for sure is that the explosion and the resulting dissipation of matter was not an act of "creation", it was not the birthday of the universe. The titanic cataclysm which may have spewed all the known worlds

and galaxies was but an episode in the evolution of eternal matter in a small region of the infinite universe.

Utterly unfounded are the attempts of some workers to restrict the universe to the region of expanding matter that can be described by Einstein's basic formulas. The universe is infinite in space and time and the part of it that the human intellect is successfully probing can no more offer an idea of the whole universe than the knowledge of how one flat in a great city is furnished can offer an idea of the furnishings of all other flats.

The expanding universe hypothesis also offers a plausible explanation of the generally vortical spiral structure of galaxies, our own Milky Way included. In an explosion eddies are always observed to trail the expanding shock-wave front. Presumably the front of our expanding part of the three-dimensional world is spreading farther and farther into the infinite space of the greater universe, of which we are as yet totally ignorant. Spiral galaxies could be viewed as vortical formations possessing a considerable degree of stability due to their great mass and the universal force of gravity. The processes of star birth and formation of planetary systems take place within the gaseous and dust clouds of these spiral galaxies.

When you see a fast-moving ship observe how whirlpools form continuously in its wake. The closer they are to the stern the faster they trail the vessel, lagging greater and greater as the distance increases. To an observer behind the ship it would thus appear that the more distant whirlpools are receding at a faster rate. The shock front of the exploding universe may be carrying along the whirlpools of galaxies in the same manner.

We may well presume that the expansion of the observable universe is a local and temporary phenomenon and that in the whole of the infinite universe there are infinite numbers of pulsating regions in various stages of expansion or contraction. But even our dream ship could not take us beyond the confines of our region of the universe to have a look at the first moment of a metagalactic explosion or a collapsing section of the universe. The spatial domains involved are much too distant for even the wildest flights of fantasy.

And that is about all that science knows about gravitational forces. This is not very much. Besides, neither Newton's classical theory of gravitation nor Einstein's general theory of relativity offer a physical explanation of why bodies gravitate towards each other at all.

PARTICLES OF GRAVITY

Einstein came to the conclusion that light propagates not in a continuous stream but in discrete packets, or quanta or photons. The existence of light quanta has been confirmed by numerous experiments and many scientists have contributed to the quantum theory. At present, when the quantum theory of electromagnetic field has been elaborated in considerable detail and the theoretical predictions have been confirmed by experiment, it is possible to hypothesize, concerning a quantum theory of gravitational field.

Before proceeding with the following discourse the authors would like to warn the reader that the propositions outlined in this section are not universally shared or accepted by the scientific community.

We shall proceed from the assumption that all bodies spontaneously emit discrete "packets of gravity", which we shall call gravitons. Let us further assume that the intensity of graviton radiation is the higher the higher the "nuclear temperature" (the energy store of the nucleus) just as the intensity of photon radiation is the higher the higher a body's temperature. The dependence of graviton radiation on "nuclear temperature" must evidently be very weak, insofar as it has never been observed.

Thus, the intensity of graviton radiation by bodies depends on the temperature, not of the body as a whole, but on the internal temperature of the component elementary particles, that is the degree of their excitation. Insofar as all elementary particles, even if they are unexcited, vibrate with a frequency of the order of 10^{22}-10^{24} cycles per second and these vibrations take place not in a vacuum, as there is no such thing, but in a field, which is a force-exerting medium, we can assume that with each pulse a

particle emits a tiny packet of energy into the surrounding environment. We can call the energy so emitted a graviton, and its matter-equivalent (which is the energy divided by the square of the velocity of light), the mass of the graviton. Finally, we assume that the number (energy) of emitted gravitons at a given degree of excitation is proportional to the mass (energy) of the emitting particle.

Imagine a hydrodynamic model in which two open pipes are placed end to end at a distance. An explosion takes place inside the pipes and the combustion gases rush out at both ends of each. The immediate impression is that in such an arrangement the pipes should be pushed apart by the gas jets. Actually, though, the reverse takes place, and the pipes are drawn together. This is because a high-pressure region develops in the space between them, the flow of gas into it decreases and the reaction force of the jets at the opposite ends of the pipes drives them together.

Now imagine two bodies radiating gravitons in all directions. The intensity of the gravitational field in the space between the bodies will, evidently, be higher than in other directions and the emission of gravitons from both bodies in the direction of higher intensity will be smaller than in other directions. The reaction force of the gravitons ejected in the opposite directions pushes the two bodies together.

In our experiment with the pipes, in addition to the reaction forces the pipes were subjected to the repellent force of the high-pressure region between them. A similar repellent force in the region of higher intensity must exist between two gravitating bodies. This force, estimates show, is immeasurably smaller than the forces of attraction. If, however, we imagine matter in a state of tremendous density, of the order of 10^{16} grams per cubic centimetre (which means that a cubic centimetre of such matter would weigh 10,000 million metric tons), the intensity and pressure of the gravitational field around two such bodies would be so great that the repellent forces would be commensurable with the attracting forces. At higher densities matter would disintegrate spontaneously and its particles would repel one another.

Insofar as a gravitational field possesses energy, and therefore mass, bodies emitting gravitons must lose both

mass and energy. As Professor D. Ivanenko first demonstrated, we can presume that two colliding gravitons can produce a particle pair, an electron and positron, for example, which can in turn change into gravitons. But for two gravitons to yield two particles in collision or, conversely, for particles to breed gravitons, such tremendous initial energies are needed that the chance of such a transmutation occurring is negligible. Spontaneous graviton emission, on the other hand, is much more probable.

Since every graviton carries away a fragment of the mass of the elementary particle to which it owes its existence, the energy of the gravitons being known, one could compute the time it would take an elementary particle to shrink by one-half. In other words, one can compute the half-life of matter in its decay into gravitational field. Such calculations have been carried out and yield values of the order of tens of thousands of millions of years. Other estimates set the mass of a graviton at the infinitesimal value of 5×10^{-66} gram, and its energy at 5×10^{-45} erg. As the mass of a proton is 1.7×10^{-24} gram (an electron is 1,840 times lighter), and the vibration frequency is about 10^{23} cycles per second, the half-life of a proton in gravitational decay is of the order of 10^{10} years. Assuming the graviton to have a density commensurable with that of the proton, which is 10^{14} gram per cubic centimetre, its radius would be about 2×10^{-27} centimetre. As the radius of the proton is 1.5×10^{-13} cantimetre, the graviton is to the proton as a speck of dust to the terrestrial sphere.

The transformation of matter into gravitons would probably depend on a number of physical conditions, notably the density of the medium and the "temperature" (energy) of the elementary components of the nucleus. When this "temperature" is relatively low a body emits less gravitons, interacts to a lesser degree with other bodies and is less ponderable. An increase of nuclear "temperature" means an increase in graviton emission and, consequently, in weight. Do "extra-heavy" and "extra-light" substances exist anywhere in the universe? Let us board our dream ship again and go in search for them.

Our destination is one of the mystery stars in the sky, the faint companion star of Sirius. As we approach it we

ment is the study of the Doppler effect in a gravitational field.

Incidentally, the hydrodynamic theory of universal gravitation may be able to explain why the force of gravity decreases faster than inversely as the square of the distance, as it should under Newton's law. This could be due to the transmutation of gravitons into other elementary particles, thus accounting for Seeliger's paradox which is giving scientists such a headache. The hydrodynamic theory of gravitation is not intended to supersede Einstein's theory of gravitational field, on which it is in some cases based. It does, however, offer a more comprehensive idea of the nature of gravity. In particular, it takes into account forces of repulsion between bodies.

IN THE HEART OF THE ATOM

Powerful and omnipotent as gravity appears to be, the domain where it reigns supreme is restricted to the macroscopic world of planets and satellites, stars and galaxies. In the microscopic world of the atomic nucleus gravitational forces are negligible, being 36 orders of magnitude weaker than nuclear field forces. This means that if we take the intensity of a nuclear field in the interactions between elementary particles as unity, the gravitational interactions between them would be expressed by a decimal fraction in which the first significant digit would appear 36 zeros to the right of the decimal point. In comparison, electromagnetic field forces are appreciable, being 100 times smaller than nuclear forces.

Hence, the first thing we can note about nuclear fields is their great intensity. Their action, however, extends over extremely small distances, and the interaction of two elementary particles 10^{-9} micron apart is practically zero. (The diameter of an atom is a thousand times greater.) The elementary particles in a nucleus interact only with their neighbours. This property, known as nuclear field saturation, has not yet been explained. It may indicate the existence of some unknown type of interaction which causes elementary particles to repel one another when

they come too close together. Yet another interesting property of nuclear fields is that the interaction between two elementary particles depends not only on the distance between them but also on the orientation of their spins.

The term "spin" was introduced as a characteristic of a particle's state at a time when elementary particles were still treated as hard little beads. Many observations indicated that they rotated on their axes, and spin was defined as the intrinsic angular momentum of a particle. The concept of spin remained after it became apparent that particles are not like hard beads, but its physical meaning changed. Nevertheless, for the sake of simplicity we can continue to treat elementary particles as spinning little beads of matter, and it is found that interactions between them depend in part on whether they approach each other with their "poles" or their "equators".

We have spoken before of heavy hydrogen, deuterium, whose nucleus comprises a proton and a neutron. This is a very stable nucleus which requires a substantial expenditure of energy to split it. Yet a deuterium nucleus can appear only when the spins of the proton and neutron are of the same sense. In this respect a nuclear field differs markedly from a gravitational field. It is rather like the interaction between two magnets in which the direction of the interaction depends on whether like or opposite poles are brought together, as well as on the mutual directions of the magnets' axes.

And one final property of nuclear interactions is that they are independent of a particle's charge. A nuclear field binds two protons as strongly as a neutron and a proton or two neutrons even though a pair of protons are subject to electromagnetic repulsion forces which act at considerable distances.

The nature of nuclear fields is still largely a mystery. There exist a number of more or less convincing theories. The most plausible at present appears to be the so-called meson theory. An electromagnetic field consists of quanta. A gravitational field is envisaged as consisting of gravitons. A nuclear field is pictured as being created by mesons, elementary particles whose mass is some 300 times that of the electron, which is why it is sometimes called a meson

field. According to the theory of Yukawa-Tamm, nuclear cohesive forces are due to a continuous exchange of mesons between elementary particles.

Little as we know about nuclear fields, whose actions determine the very existence of matter, our knowledge of the atomic nucleus is steadily expanding. There can be no doubt that the time is not far off when all its secrets will be unravelled and nuclear fields will serve man as tamely and faithfully as electromagnetic fields do today.

FACTORIES OF MATTER

For centuries generations of medieval alchemists devoted their lives to attempts to turn mercury and other common elements into gold. They spent days and nights in their vaulted basements manipulating with flasks and retorts, dissolving, burning, evaporating, combining and separating various substances in a futile quest for a short cut to wealth. What sudden inspirations, promising discoveries, bitter disillusionments and dashed hopes they experienced! In all of science only the idea of perpetuum mobile (perpetual motion) has taken such a great toll of fruitless endeavour. Perpetual-motion machines are indeed impossible and will never be created. Not so the transformation of one chemical element into another. This problem has been solved and today physicists are actually creating new elements that are not found on earth. To date they have added 11 new elements to the 92 in the Periodic Table. The day will surely come when industrial plants will be built for manufacturing rare elements out of abundant elements.

The transformation of chemical elements is caused by changes in their nuclear structure. The atomic nucleus is shielded by a powerful electromagnetic field and by one or more electron shells. It takes a tremendous force to penetrate these barriers. Atomic nuclei are literally bombarded with elementary particles, usually hydrogen nuclei accelerated to velocities approaching the speed of light in giant electromagnetic installations. One of the biggest particle accelerators in the world is operating in the town

of Dubna, not far from Moscow. It is called a proton synchrotron and is capable of imparting energies of up to 10 Bev (billion, or thousand million, electron volt) to the accelerated particles. More powerful installations are being built and one under construction in the U.S.S.R. will have an energy capacity of 50-70 Bev.

Another method of breaking down the armour of the atomic nucleus is the thermal acceleration of particles. The one known method of heating a substance to temperatures sufficient to make atomic nuclei collide is in the explosion of an atomic bomb.

It is also possible to penetrate into the atomic nucleus with neutrons. Neutrons have no charge, which enables them to approach the atomic nucleus at a relatively slow speed. A neutron entering the nucleus is capable of causing a nuclear transformation. Such reactions can occur in nature. Cosmic rays, for example, are powerful streams of elementary particles accelerated to fantastic velocities, and they can well provide the energy needed for the creation of different elements. Cosmic rays reach the earth in fairly steady streams, but at times their intensity jumps sharply. This happens shortly after astronomers observe flares on the sun, which usually occur in the vicinity of a group of sunspots. A flare lasts only a few minutes but it erupts great cascades of cosmic rays which collide with ions in the sun's atmosphere and produce new elements.

Two or three decades ago it was estimated that the internal temperature of stars must be as high as ten or twenty million degrees. This is sufficient for the synthesis of helium from hydrogen nuclei, but it is not enough for the creation of heavier elements. In recent years it has been found that intrastellar temperatures may be much higher. In the course of the "burning out" of hydrogen into helium a star stratifies as it were. It develops a dense hot core, with hydrogen continuing to "burn" at its surface, and a relatively cool, greatly expanding envelope. Computations show that temperatures of the order of 150 million degrees C are possible within the cores of "burnt out" stars, which is sufficient for the formation of oxygen, neon and other elements of the Periodic Table up to calcium. The creation of heavier elements requires temperatures

of thousands of millions of degrees. They are yielded in the explosions of "new" and "super-new" stars—*novae* and *supernovae*, which we shall discuss later on.

We have listed three ways in which nuclear reactions may be effected: by the electromagnetic acceleration of elementary particles, by the thermal acceleration of nuclei, and by the "cold" penetration of neutrons. The latter method is probably paramount in element production processes in the interiors of "burnt out" stars. The theory of this process was developed by Cameron in Canada and Greenstein in the United States. Direct observations confirm that the creation of elements is in fact taking place within stars today.

One proof was provided by the Soviet astrophysicist G. A. Shain, who discovered an unusual abundance of a carbon isotope in the spectra of certain stars. This could only be a result of continuous nuclear reactions within the stars.

Another proof was the discovery of bright lines of technetium in some stellar spectra. Technetium is an unstable radioactive element with a half-life of several hundred thousand years. If it ever did exist on earth it long since disappeared through radioactive decay. It was first produced artificially by the Italian scientists E. Segre and C. Perrier working in the United States. Technetium is not a product of natural nuclear fission reactions and it can be produced only in the melting pots of thermonuclear fusion reactions. The appearance of technetium in stellar spectra is as sure a proof of the creation of atomic nuclei inside those stars as smoke from a chimney is proof of a fire in the stove.

CONTINENTS AWAITING THEIR COLUMBUSES

Can we claim to know all the forms of matter and types of field with the same assurance that we can assert that there are no undiscovered continents on earth? After analysing photographs of distant galaxies made with the world's biggest telescope, the Soviet astronomer B. Vorontsov-Velyaminov came to the conclusion that their

shapes could not be explained solely on the basis of the forces and fields known to us. He accordingly postulated the existence of an unknown field of repulsion detectable only on a metagalactic scale. The present authors do not agree with this hypothesis. They hold the view that the shapes and interactions of galaxies can be explained by electromagnetic and gravitational field interactions alone.

That is as it may be, but there is data that point to the existence of manifestations of matter still unknown to us. We still know very little about the plasma state of matter at high temperatures. We apply the name "plasma" to a match flame, the fireball of a nuclear blast and the substance of exploding stars with temperatures of billions of degrees. Yet plasma is not a homogeneous entity. The higher its temperature the greater the number of charged particles and photons, which are carriers of energy. It may well be that at some stage in the accumulations of quantitative temperature changes there occurs a qualitative jump, and plasma turns into a new and unknown state.

As is known, absolute zero is the lowest limit temperature can reach (the existence of absolute zero temperature was predicted theoretically, and later almost reached experimentally). On the other extreme, however, there appears to be no maximum temperature limit. But is this really so? Moreover, is it possible? After all, there exists a limiting velocity, and temperature is determined by the velocity of moving particles. It would seem that the maximum possible temperature should be given by the motion of particles with the speed of light. Reality, however, is not so simple. One of the corollaries of the theory of relativity is that a body's mass increases with its velocity, tending to infinity when the velocity approaches the speed of light. No particle possessing mass can travel with the speed of light.

One could expect, though, that matter comprising particles moving with velocities approaching that of light, whose mass is much greater than their rest mass, should display some entirely new qualities. This could be a new state of matter, and stars and nebulae made up of such matter might well be existing somewhere in the universe.

New states of matter may be envisaged in antimatter, which is matter constituted of antiparticles. The existence of antiparticles was predicted by the English physicist Paul Dirac, and they have recently been produced in giant particle accelerators. Antimatter may exist in the known states of solid, liquid, gas and plasma, and it may also have peculiar states of its own. Man has only just begun to open the door leading into the "looking-glass" world of antimatter. There can be no doubt that future explorers will make many discoveries in that unexplored country.

Pressure, too, can increase unlimitedly, and within giant stars matter may be compressed to an unimaginable degree. One can picture the behaviour of an atom subjected to a steadily increasing pressure. First the outer electrons, which determine its valency and ability to enter into chemical compounds, are crushed into the underlying electron shells. This takes place at the relatively small pressure of several hundreds of thousands of atmospheres obtainable in terrestrial laboratories. The atom does not lose its identity and retains its chemical properties as an element. A further pressure increase to millions of atmospheres deprives the atom of its chemical identity and the atoms of all elements are reduced to a universal metallic state, which can be found in the cores of planets, the earth included.

Investigations of the propagation of shock waves caused by earthquakes or manmade explosions reveal two boundaries inside the earth at which the properties of matter change drastically. The first lies at a depth of 15 to 75 kilometres, the second at about 2,900 kilometres below the surface. Above the first boundary matter is found in its conventional solid state. Between the first and second boundaries the pressure probably increases from 50 to about 100,000 atmospheres. Below 2,900 kilometres it probably exceeds one million atmospheres. The boundaries demarcate the points at which the gradual increase in pressure produces a sudden change in the states of matter.

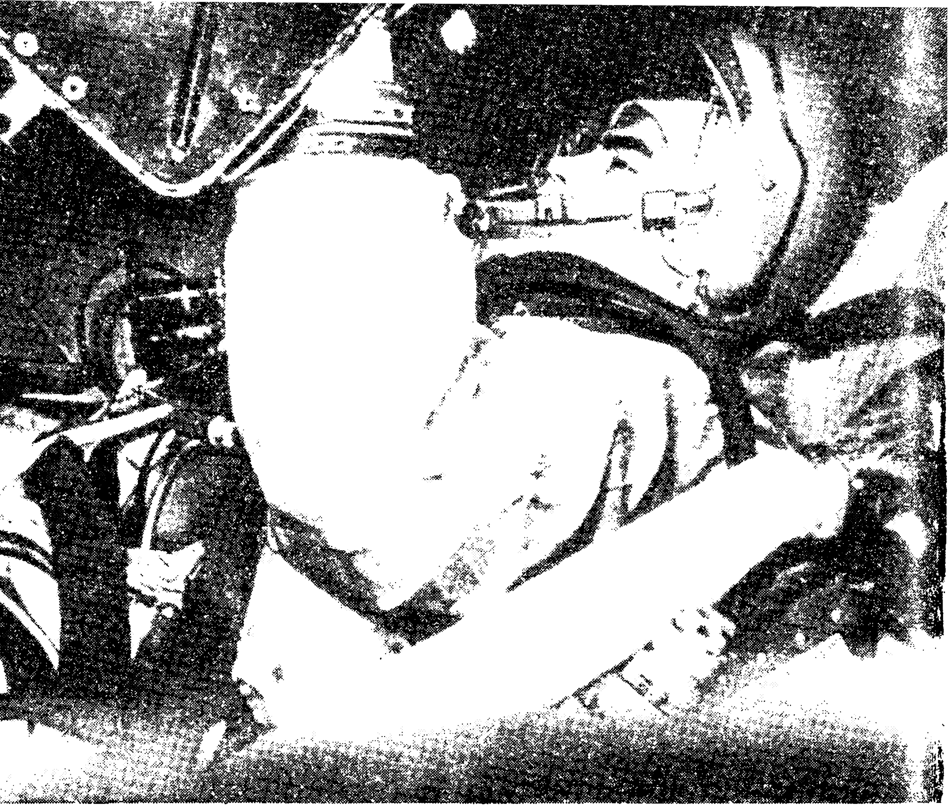
The earth's core, which begins 2,900 kilometres below the surface, does not transmit transverse waves, behaving like a liquid in this respect. But as it could hardly be liquid we must assume that at the great pressures to which

it is subjected the orderly spacing of atoms that occurs in solids is impossible. The matter of the earth's core may be in some unknown state. The internal pressure of the moon hardly exceeds 50,000 atmospheres. Therefore the moon has no "metallic" core, which would explain the absence of an observable magnetic field.

Matter serves man in many ways, but it continues to harbour many secrets. And as Albert Einstein put it, "the feeling of mystery gives use to some of our best and deepest emotions... He who does not feel these emotions, he who has lost the ability to wonder and falter in anticipation is as good as dead."

Great are the undiscovered secrets of nature. Not islets or coral reefs hardly rising above the surface of the ocean, but whole continents of unexplored phenomena are awaiting the Columbuses who will discover them.

Machines
of rays and jets



Andrian Nikolayev, Soviet cosmonaut, during his orbital space flight

A JOURNEY INTO THE DAY AFTER TOMORROW

Let us board our time machine again to take a trip into the future and see how some machines have evolved since our time. Slowly we push the control bar from the zero position. The years flick by on the speedometer. Our destination is March 2065.

We are in the street of a beautiful city. Colourful flowerbeds line the pavement. A bright luminescent cloud billows in the sky. On a plastic bench sits a young man and talks into a small box the size of a cigarette holder. What can it be?

Obviously, one could ask more questions about that world of the future than could be answered in a much bigger book than this one. Our interest is to see how the different states of matter and fields serve men of the 21st century. Some things we can guess ourselves, but we must ask the people of the 21st century for an explanation of others.

To begin with, the little box in the man's hand is a pocket two-way T.V. set, a video walkie-talkie. It has three control knobs. One is for switching on any of several hundred radio wavelength channels through which one can contact with one's friends or business associates who also have video walkie-talkies in their pockets. The second knob is for image sharpness control, which comes in handy if one wishes to show a book illustration, or a microscope slide, or a scene of some kind. The third knob is for volume and image brightness control. Every owner of such a set has a wavelength of his own assigned to him. This became possible when man mastered radio wavebands of extreme ultrahigh frequency.

Now about that ball of fire pulsating in the sky. This, we find, is a manmade sun lit up at the intersection of several beams of electromagnetic radiation. The beams are generated in huge bowls some 100 metres in diameter. The cloud of plasma hovering 30 kilometres over the city is heated to several tens of thousands of degrees. The size of the cloud, its temperature and heat radiation are easily regulated by adjusting the intensity of the electromagnetic beams. In winter the artificial sun is "hottened up" and kept alight round the clock. In summer it is switched on only at night for illumination. An important feature is the control of the artificial sun's spectrum, the content of ultraviolet and infrared rays in its radiation. Thanks to it people no longer need winter clothes, and plants bloom in all seasons. In other words, the people of the 21st century control the climate in big cities. This became possible thanks to the abundance of power supplied by thermonuclear electric stations.

Small one-man flying machines flit about over the city streets. Their rotors are powered by a high-frequency electromagnetic field emitted by special antennas.

One of the most interesting things we saw in the future world, however, was a T.V. feature entitled *The Century of Astronautics*. We saw it right in the street on a huge concave screen some 30 metres high. It was no more than 20 centimetres thick, and its roughened surface gleamed dully. When the broadcast began it seemed to melt away. It is impossible to describe the striking three-dimensional

effect. In place of the screen there appeared a window through which we looked out into a living, tangible world.

At the beginning of the feature a portrait of Konstantin Tsiolkovsky, the man who first pointed out the road to the stars, was displayed. Well, it is only natural that the people of the future should pay homage to the one who began the great work. They also remembered Nikolai Kibalchich who, long before Tsiolkovsky, in a solitary dungeon of the Fortress of Peter and Paul, made the first drawing of a rocket-propelled machine. Then began the story of those who continued the trailblazers work, of the flights of the first jet planes, geophysical rockets, up and until the first triumph over gravity.

The year 1957. The grey body of a rocket slowly rises on a fiery column of exhaust gases. It accelerates and disappears into the sky to place Sputnik 1, the world's first artificial earth satellite, into orbit.

The beginning of 1959. A rocket is launched in the direction of the moon to become the first manmade planet. Some truly remarkable sequences follow. A spaceship of the future meets the first manmade planet in the depths of interplanetary space. Its flight has been filmed from the spaceship.

"It will continue in its orbit between Mars and Earth for hundreds and thousands of years", the narrator remarks. "But the day will come when man will bring it back to earth and place it in a museum along with the most treasured relics of human culture. With a feeling of awe and gratitude people will read the proud inscription on the pennant: 'Union of Soviet Socialist Republics. January 1959'."

Many dates flit by on the screen. The first rocket to deliver a Soviet pennant to the moon. The first photographs of the far side of the moon taken by an automatic probe. The first space flight of Yuri Gagarin. The first scientific expedition to the moon. Exploration of Mars. Venusian landscapes. Installation of a sun service station on Mercury, the closest planet to our central luminary. The leap to the satellites of Jupiter and Saturn. Landing on Pluto...

The breathtaking advances of astronautics in these hundred years made possible the new discovery of the solar system. The narrator goes on to describe the designs of spaceships. The first flights, including the visits to Mars and Venus, were carried out in rockets propelled by chemical fuel. The design of their motors is well-known. Separate tanks carry the propellant and the oxidizer. Pumps deliver them to the combustion chamber. On the way they cool the walls of the nozzle and the chamber in which the simplest form of energy, heat, is produced in a turbulent chemical reaction. The incandescent ball of gases seeks a way out of the crowded combustion chamber, finds it and rushes through the exhaust nozzle, which performs the important job of transforming the unorganized heat motion of material particles into the organized motion of a gas jet. Heat energy is transformed into the mechanical energy of the rocket's motion.

On the screen we see these first vehicles, which carried men to the neighbouring planets. Giant multistage rockets packed almost completely with propellant. The passenger and cargo space accounts for no more than one-thousandth of their volume. Even so they were comparatively slow vehicles. It was all they could do to pass the escape velocity of 11-12 kilometres per second, enabling them to overcome the earth's gravitational pull and start coasting in the gravitational field of the sun. Their takeoff

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Mathematically speaking

THE FUNDAMENTAL ROCKET FORMULA

Konstantin Tsiolkovsky showed that if a small quantity of gas of mass Δm is ejected from a rocket nozzle with a speed v, a rocket of mass m will acquire the velocity

$$\Delta u = v \frac{\Delta m}{m}$$

If the mass ejected during the operation of a rocket motor is M, the final velocity of the rocket is given by the formula

$$u = -v \log_e \left(1 - \frac{M}{M_0}\right) = -2.3 \log_{10} \left(1 - \frac{M}{M_0}\right)$$

where M_0 is the initial mass of the rocket. This formula can be conveniently rewritten:

$$\frac{M}{M_0} = 1 - e^{-\frac{u}{v}} = 1 - 10^{-0.43\frac{u}{v}}$$

trajectories were calculated to permit them to cover most of the distance from planet to planet with their motors switched off. The first astronauts had only just enough propellant for them to land on and take off from a strange planet.

Then came atomic vehicles. The principle of their motors is also fairly simple. They, too, have a nozzle like that of the chemical propellant rocket. Only instead of the combustion chamber there is an atomic reactor. One way of heating water in the reactor of an atomic electric station is by passing it through uranium pipes. A spaceship reactor also uses uranium pipes. Gas passing through them becomes heated and "works" in the exhaust nozzle. Instead of propellants, the rocket carries a stock of a chemically inactive substance, water for example. A nuclear motor of this type would not make for a substantial increase in speed, if it could operate at all. A rocket's speed depends on the velocity with which the gases are ejected through the nozzle, which in turn depends on the temperature of the gases in the combustion chamber: the velocity of the jet appears as a result of the transformation of the heat energy of the gas into the mechanical energy of motion. Hence, the higher the temperature of the gas in the combustion chamber the greater the velocity of the jet. At 2,500°C the speed of ejection may reach 3,000 metres per

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where $e=2.72...$ is the natural logarithm base.

If the velocity of the gas jet, v, approaches the speed of light, which may be achieved in future nuclear-powered motors, special relativity must be applied, and Tsiolkovsky's initial formula takes the form

$$\frac{\Delta u}{1-\frac{u^2}{c^2}} = v\frac{\Delta m}{m}$$

where u is the velocity of the rocket and c the speed of light.

Tsiolkovsky's second formula can be written:

$$\frac{M}{M_0} = 1 - \left(\frac{1-\frac{u}{c}}{1+\frac{u}{c}}\right)^{\frac{c}{2v}}$$

or

$$\frac{u}{c} = \frac{1-\left(1-\frac{M}{M_0}\right)^{\frac{2v}{c}}}{1+\left(1-\frac{M}{M_0}\right)^{\frac{2v}{c}}}$$

second. At 25,000° the speed of ejection could rise to 10,000 m/sec.

But then, no substance can withstand such a temperature. This problem is one of the main stumbling blocks for the use of atomic fuel in the middle of the twentieth century. Metallurgists are searching for superrefractory alloys. Very slowly they are climbing up the temperature scale. Designers resort to all sorts of ingenious devices to cool the walls of combustion chambers and separate them from the fiery breath of hot gases by some means or other. For example, they make the chamber and nozzle walls porous and squeeze liquid propellant through the pores into the chamber. The propellant evaporates, cools the metal of the walls and forms a thin layer of cool vapour. The incandescent gases are wrapped up in this nebulous packing, which travels with them to the cooler part of the jet.

In a nuclear reactor, on the other hand, the walls of the uranium pipes must be heated to a temperature higher than that which we wish to impart to the "working" gas. Although in principle it is possible to raise the temperature inside the reactor as high as we wish we should not forget that uranium itself melts at 1,133° C. Of course, one can envisage a reactor working on liquid and even gaseous uranium. But where are the substances capable of containing uranium plasma at a temperature of, say, 10,000 degrees? Besides, the control of such a uranium-

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In the case of a photon rocket, $v=c$, and these relationships take the simpler form

$$\frac{M}{M_0} = 1 - \sqrt{\frac{1-\frac{u}{c}}{1+\frac{u}{c}}};$$

$$\frac{u}{c} = \frac{1-\left(1-\frac{M}{M_0}\right)^2}{1+\left(1-\frac{M}{M_0}\right)^2}$$

For example, if 90 per cent of the rocket's total mass is burnt out, i.e., $\frac{M}{M_0}=0.9$, we have $\frac{u}{c}\approx 0.98$. The mass expenditure can be linked with the time dilation in the rocket. As the time dilation depending on velocity is given by the formula

$$t' = t\sqrt{1-\frac{u^2}{c^2}}$$

where t is the terrestrial and t'

plasma reactor, which at any moment might turn into an atomic bomb, would present some formidable problems.

But suppose we do build a reactor capable of providing the necessary temperature for the pipes carrying water vapour to the exhaust nozzle. The task is to ensure that the vapour heats to the required temperature in the few moments it takes to pass through the pipes. Hydrogen has a high thermal conductivity, but its density is very small, and an adequate supply for a space flight would take up too much place. That is why nuclear rocket designers have suggested water as the inert substance. It decomposes under the high temperature into oxygen and hydrogen, and the heat conductivity of this mixture is adequate.

The television feature describes several variants for solving the problem suggested at different times. In one the reactor is aligned with the nozzle. The gas is heated to the highest possible temperature at the entrance to the nozzle. It accelerates in the nozzle, its pressure drops, but the temperature is kept at the same level by heating. In this design the gas receives the thermal energy to be converted into the mechanical energy of the exhaust jet not all at once, but in several batches. A batch of heat is

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is the rocket time, the connection between the burnt-out fuel and time dilation takes the form

$$\frac{t'}{t}=2\,\frac{1-\frac{M}{M_0}}{1+\left(1-\frac{M}{M_0}\right)^2}$$

For example, if 90 per cent of the mass is burnt out, i.e., $\frac{M}{M_0}=0.9$, we get $t'=0.2t$, i.e., the passage of time in the rocket is five times slower than on earth.

An analysis of the formulas reveals that only at a jet velocity of $v\approx c$ can substantial speed be attained for reasonable ratios of $\frac{M}{M_0}$. Even at $v=15{,}000$ km/sec, the amount of fuel to be burnt to achieve a rocket velocity of 100,000 km/sec would be more than any technically feasible project could cope with:

$$\frac{M}{M_0}=1-\left(\frac{1}{2}\right)^{10}\simeq 1-0.001$$

This means that 0.999 of the total mass would have to be burnt out to accelerate the remaining 0.001 part to the required velocity.

injected and transformed into mechanical motion, then another batch is injected, and so on. In this way it is in principle possible to accelerate the gas jet to any desired velocity. In practice, however, such a motor, which would have to have a very long diverging nozzle, would be difficult to build.

In another variant hot vapourized uranium is injected into a stream of inactive gas. On the way through the nozzle it mixes with the gas, gives off its heat and condenses into tiny droplets which then solidify. But uranium is too costly a product to throw out with the exhaust gases, so the uranium dust is separated and returned to the reactor. Thus it circulates, heating in the reactor and cooling in the jet. However, this scheme is also too complicated for implementation.

It is not so easy to design a nuclear spaceship. A rocket requires fast acceleration and its motor must possess a very powerful thrust. For a rocket to reach the escape velocity of 11-12 km/sec in 400 seconds, its thrust per kilogram of payload must be 10 times greater than the power capacity of atomic reactors of the mid-twentieth century. A reactor capacity of millions of kilowatts would be required to place a rocket on the moon. Today the biggest reactors have capacities of hundreds of thousands of kilowatts. Nevertheless, the nuclear rocket motor was built. We missed the date of that new triumph of science and technology, which flicked by too rapidly on the screen.

The feature goes on to show the launching of the first nuclear spaceship. The relatively low weight of the nuclear fuel made it possible to operate the motor for much longer periods of time. The possibility of switching it on in flight served to raise the "cruising" speed to more than 50 km/sec. The duration of flights became less, the trajectories of space vehicles became shorter, and astronavigation changed. The end of the 20th and first quarter of the 21st century saw the rise of nuclear-powered interplanetary ships which made it possible for man to visit all the planets of the solar system.

"And now what?" the narrator asks. "Will man halt at the edge of the void separating stellar systems? Will the scientific station on Pluto, the most distant planet

of the solar system, remain man's farthermost outpost in the universe?"

A strange landscape appears on the screen. Bluish-green cliffs look as if they are made of ice with outcroppings of giant crystals. A brightly illumined tunnel leads into a manmade cavern. A spaceship stands on its launching pad. A small, weak sun shines from somewhere behind and the shadow of the spaceship on the floor of the valley looks like a road into the unknown. Several men wearing space suits stand on an overhanging platform and look in the direction of the shadow.

"Our travels within the solar system were journeys along brooks and rivers," the narrator says. "Today we stand on the shore of the Great Ocean."

There is no comparison between interstellar and interplanetary distances. Draw a circle 15 millimetres in diameter on a sheet of paper. This is our solar system. On this scale we could not see the specks representing the planets even under a microscope. The sun itself would be less than a micron in size. At what distance do you think you would have to draw another circle to denote the planetary system of the closest star? The sheet of paper is not enough, nor the floor of your room, nor indeed the boundaries of your town, if it is not big enough. The closest star to the sun on the scale mentioned would have to be 30 kilometres away. The actual distance is 40,000,000 million kilometres. It takes a ray of light travelling with a speed of 300,000 km/sec 4.27 years to span it. Such is the interstellar scale. A trip in an interplanetary vehicle of the last quarter of the 20th century, which makes 30-40 km/sec, would take 2,000 years. Even the best nuclear spaceships of the mid 21st century, which travel three times faster, would take 700 years for a one-way journey. In short, the problem of interstellar flight cannot be solved with spaceships powered by chemical motors, uranium motors, nor even the most sophisticated thermonuclear motors. Their thrust is much too small and the vehicles are much too slow for the vast distances involved. And yet, interstellar flight is possible!

TAKEOFF FROM THE ASTEROID PALLAS

Our story of the science feature shown on the magic screen of the 21st century is rather fragmentary. It is impossible to retell it all, but the parts telling of the discoveries made in the world of elementary particles are of special interest. The logic of dialectics is such that discoveries in the microcosm of extremely small things have contributed to the mastery of the macrocosm of huge things. They point to the ways and means of carrying out interstellar flight.

We already know that in the first quarter of the 20th century all substances in the world were thought to consist of electrons—light negatively charged particles, and protons—heavy positively charged particles. Then the number of new elementary particles began to grow at a startling rate. There appeared heavy particles carrying no charge, neutrons; light positively charged positrons; mesons of all kinds; fantastically elusive neutrinos; photons, the elementary particles of electromagnetic field; and a whole family of hyperons. Then with the help of giant machines capable of accelerating elementary particles almost to the speed of light people produced so-called antiparticles. Among them was the antiproton, a heavy particle carrying a negative charge, and the antineutron, whose difference from the ordinary neutron lies not in the particles' nonexistent charge but in "mirror symmetry" of other properties peculiar to elementary particles.

By the middle of the 20th century scientists were already asking whether it would not be possible to create "antiatoms" with negatively charged nuclei surrounded by clouds of positrons. What properties would substances made of such atoms possess? Would they arrange themselves into a Periodic Table of antimatter? It might be a good idea, some workers said, to take a closer look at distant galaxies to see if some of them were not made up of antimatter. For all we know, the inhabitants of some planet in a stellar system of a remote galaxy may have just produced "anti-antiparticles" in their superpowerful accelerators and are wondering if there could possibly exist worlds in which "antipositrons"—elec-

trons, that is—circle around positively charged nuclei. Many of these surmises and conjectures of the 20th century are answered in the feature being shown on the magic screen of the 21st century.

Antimatter can be produced, and in a vacuum devoid of particles of ordinary matter, even though it is permeated with fields, it will be as stable as ordinary matter. But the two cannot come into contact. They are bitter antagonists, which explains the short life of antiparticles produced in giant accelerators. A collision between similar opposite numbers results in the annihilation of both particles with the emission of photons. Similarly, if an ordinary atom comes into contact with an anti-atom the two explode with the emission of other particles and a greater energy output than in the fusion of hydrogen nuclei into helium.

We have already mentioned that one of the corollaries of Einstein's general theory of relativity is the mass-energy equivalence. A glass of hot tea weighs more than the same glass of cold tea, a flying bullet has a greater mass than it did before it was shot. Transformations involving the evolution of energy result in a reduction of the mass of the substances concerned. The correlation between mass and energy is such that huge quantities of energy correspond to very small quantities of mass. Thus, were we to collect all the products from the combustion of several trainloads of coal, which a thermal electric station burns in a day—all the gases, cinders and ash—we would find that they weigh only about 0.05 gram less than the burned coal. This is the "mass" of the electric energy produced by the plant.

Not so with nuclear fuels. Their energy-to-mass ratio is much greater and the "mass defect", as it is called, lends itself to observation. In the fission of uranium nuclei, for example, it is equal to 0.05 per cent. In the fusion of hydrogen into helium it is as high as 0.9 per cent, that is to say, 9 grams per kilogram of matter, a quantity that is readily measurable.

In the interaction of a nucleus of matter with one of antimatter practically the whole of their masses turn into electromagnetic field quanta and other types of ra-

diation. True, the transformation is not instantaneous, and it takes the form of a series of transmutations of mesons of various kinds. The energy evolved is almost a hundred times greater than in a hydrogen fusion reaction.

The makers of our 21st-century scientific feature needed this excursion into the world of elementary particles in order to broach the idea of the theoretically most powerful motor possible, the only kind of motor capable of taking earthmen to the nearest star, Proxima Centauri.

A diagram of a spaceship appears on the magic screen. It is a huge structure. One vast chamber is equipped for storing antimatter in the form of powdered anti-iron, which an electromagnetic field keeps suspended in space so that not a single particle comes into contact with the walls. By altering the intensity and shape of the magnetic field the powdered anti-iron is delivered in small batches into the "combustion" chamber. On the way a high-frequency electromagnetic field heats and vapourizes the powder. (Preliminary vapourization is needed to ensure the complete annihilation of the fuel, in which every antiparticle would collide with its counterpart.) In the "combustion", or rather annihilation, chamber the vapourized anti-iron meets with vapourized common iron (injected without such precautions). A blinding flame dances at the meeting point of the two jets and incredible quantities of energy, mainly radiant, evolve inside a very small volume of space. A collision between two chunks of matter and antimatter would, of course, also produce an explosion, but the reaction would involve only the particles at the place of contact. Most of the masses would be hurled apart and the annihilation would stop.

According to another project the antimatter is manufactured inside the spaceship in sophisticated apparatuses deriving from the particle accelerators we know today. The newly created antiparticles are then injected into the annihilation chamber. How is this chamber designed to impart the required thrust to the spaceship?

As a matter of fact, there is no chamber as such. The pipes and magnetic pumps which deliver the matter and antimatter extend outside the rocket's stern into the focus

of a giant parabolic mirror. The radiation generated in the annihilation reaction is reflected from the mirror in such a concentrated beam that it is capable of vapourizing metals crossing it millions of kilometres away. This mirror is the spaceship's sail.

Back in 1900, the Russian physicist P. N. Lebedev demonstrated that light exerts pressure. In ordinary conditions it is not very great, and sunlight reaching the earth exerts a pressure of no more than one-half of a milligram per square metre. However, the intense flux of photons generated in matter-antimatter annihilation exerts a sizeable pressure capable of giving substantial impetus to the spaceship.

These ideas, though, relate to the future, even from the point of view of men of the 21st century. In their spaceships the combustion chamber is like the electromagnetic "bottle" discussed before. Like a conventional bottle it has a narrow neck opening sternwards which does the work of the nozzle in "conventional" rocket motors. Inside the electromagnetic bottle a sustained thermonuclear reaction is taking place and the charged plasma particles rush out of the nozzle. To increase the temperature of the plasma, and hence the velocity of the reaction jet, some 10 per cent of powdered antimatter is injected into the thermonuclear flame.

And now the design of the whole rocket appears on the screen. We observe that interstellar ships, too, are multistaged vehicles which jettison their ballast of emptied hydrogen tanks. Such a vehicle is capable of attaining a velocity of 250,000 kilometres per second, five-sixth the speed of light.

"The crew of the stellar ship will be able to reach Proxima Centauri in only five years," the narrator informs us. "It will take another five years to return to the solar system. If the astronauts spend five years exploring the planets of Proxima we can expect them back within fifteen years. This is not too great a time, especially if we remember that only five hundred years ago it took Magellan's expedition three years to circumnavigate the globe for the first time." The feature ends. For several moments the silvery-white screen quivers in the waves of unborn

images. Then the face of the narrator appears. In a voice ringing with emotion he announces:

"In ten minutes' time an interstellar spaceship will be launched from the asteroid Pallas. We shall now bring you a direct telecast of the launching."

The interstellar ship, lit up by brilliant searchlights, is poised for the launching. The tiny, rocky world, no more than 500 kilometres in diameter, has served as the base for its construction, or rather assembly, although some indigenous asteroid rock was also used. It took five terrestrial years to assemble the rocket on the asteroid. Now it has been towed several tens of kilometres out into space: the blastoff could endanger the builders and the asteroid itself if the motor's exhaust jet hit the ground.

The vechicle is not at all streamlined, as one might have expected. The main body is a bundle of huge cigar-shaped tanks several tens of kilometres long. Moored to it are several "conventional" spaceships for exploring the planets of Proxima. Doughnut-shaped living quarters in which the centrifugal forces of rotation generate a synthetic gravity. Spherical laboratories and hothouses. A twin-layer antimeteor shield in front of the vessel, which will move in its "shade". Thanks to the speed of travel the shield will ward off oncoming meteorites, sweep aside those coming in at an angle and overtake those moving in the same direction.

The measured beat of a metronome counts down the final seconds before blastoff. Suddenly it stops and a white blade of fire shoots out of the stern. Like the recoil of a spring, it hurls the vessel forward. Gradually the spaceship accelerates. It passes broadside across the screen. Now we see it from the rear and the jet of flame seems to be directed towards us. Several minutes pass and the flame goes out. The spaceship has attained a velocity of 70 km/sec. It follows the broad sweep of a hyperbola to the outer confines of the solar system. After a final checkup of all working systems the crew will switch on the motor for acceleration to sub-light speed. The screen dims. The story of developments in the 21st century is over and it is time for us to return to our own time. Switch on our time ma-

chine's motors and head it "downwards" through time! Let us sum up our impressions.

In the 21st century matter continues to serve man in all four states—solid, liquid, gaseous and plasma. The share of plasma has increased substantially. It is used in the toruses of thermonuclear power plants, in artificial suns hovering over cities and in the flame ejected from the magnetic "bottle" of spaceship motors. Applications of electromagnetic field have increased. Recall the video walkie-talkie and the high-frequency field which powers the flying craft that have replaced municipal transport systems. Recall that directed beams of electromagnetic radiation kindle the artificial sun. Recall also the magnetic chamber of the spaceship and the great television screen. Nuclear fields also serve people of the 21st century in thermonuclear plants and the reactors of interplanetary and interstellar ships.

TRIP TO THE STARS

The boost stage of a rocket carrying an artificial earth satellite aloft lasts only a few minutes. The reason is obvious: the greater the acceleration the faster the required velocity is achieved, the more powerful the motor the less the expenditure of fuel. For passenger spaceships, however, the acceleration is restricted by the limits of physical endurance of the human organism. The earth's gravitational pull, it will be recalled, increases the velocity of a freely falling body by 9.8 metres per second for every full second that it is applied. This is the so-called acceleration of gravity at the surface of the earth, which determines the weight of body on the ground. If the acceleration of a rocket is 50 metres per second (m/sec^2) the increase in the so-called G-load is fivefold, and a man of 70 kilograms will weigh 350 kilograms. This load is endurable over a brief period of time, but greater accelerations are dangerous.

Suppose a spaceship has to attain a velocity of 100,000 km/sec. Obviously, it cannot be reached in a few minutes and, in fact, this is not even necessary. A

starbound spaceship will not take off from the earth, where it must break away from the pull of gravity as quickly as possible. The launching will take place in outer space, where Tsiolkovsky's formula, according to which the velocity developed by a space vehicle depends only on the velocity of the exhaust jet and the amount of burnt propellant, is applicable. Even a blow torch, which, of course, will not fly off unless thrown by an irritated worker, could in conditions of outer space—given sufficient time—accelerate a space vehicle to the required velocity. So what thrust must the motors of a starbound spaceship have and what acceleration will it travel with?

The answer to the second half of the question is, only 10 m/sec^2. This is the acceleration to which the crew is accustomed on earth, and every man in the craft will feel himself no heavier than on hard ground. In 123 days of continuous operation the motors will accelerate the spaceship to the cruising speed. Much space will be covered in this time. As much, in fact, as it would take a beam of light to cross in 506.5 hours, or 21 days. This, of course, is only just over one-hundredth of the distance to Proxima.

Earthmen have never travelled at such speeds and the members of the crew will evidendly experience many novel sensations. They will notice a marked change in the stars about them, as their spaceship gains speed. The ones directly behind the spaceship will get redder and redder until they "go out" altogether. This is a direct consequence of the Doppler effect, owing to which the visible spectrum shifts towards the invisible infrared region of the spectrum. For the same reason the stars directly ahead will turn violet and also disappear from sight. Unchanged remain only the stars lying within a narrow band of the sky displaced slightly to the stern of the spaceship. Behind it the stars are weirdly red, in front they are like glowing blots of purple ink. The greater the velocity, the narrower the band of visible stars and the more towards the stern it is displaced. At the velocity of light, should that be possible, the band would turn into a point directly behind the spaceship.

Our vessel is travelling at a speed of 100,000 km/sec. It will spend twelve and a half years in flight, but what with research work, determination of the positions and motions of stars, the study of stellar spectra, experiments with gravity, and so on and so forth, time will not hang heavy on the crew's hands. They will also have to devote much time and effort to protect themselves from the hazards of outer space. Principal among them is the meteoroid hazard.

A young Soviet scientist, F. N. Yasinsky, has suggested an interesting method of combatting it. The spaceship should carry in front a thin metal "umbrella" slightly bigger in diameter than the body of the vehicle. Obviously, if the vehicle is at rest the "umbrella" will offer protection only from meteoroids coming head-on. But if the vehicle is travelling faster than the meteoroids the "umbrella" casts a "shadow" entirely free from meteoric particles. Those coming head-on will obviously encounter the "umbrella", those coming in from the side will be swept away, and those trailing the ship will never catch up with it. Small particles will not harm the "umbrella" very much. On impact the kinetic energy of the particles will instantaneously turn into heat, and the meteoroids and bits of the "umbrella" will turn into a cloud of rapidly expanding gas. How great can the erosive effect of interstellar matter be and how long will the "umbrella" withstand it?

Although the density of interstellar space is only about 10^{-24} gram per cubic centimetre, which is to say that every cubic centimetre of space contains about one atom of hydrogen, at speeds approaching that of light every square centimetre of the rocket's greatest cross section will sweep through an estimated 3×10^{-14} grams of matter per second. The energy of the continuous impacts will amount to some 3×10^{7} erg/cm^2 sec. The energy evolved in the explosion of 1 gram of TNT is about 4×10^{10} ergs. Thus, each second every square centimetre of Yasinsky's "umbrella" will be subjected to the equivalent of an explosion of one-thousandth of a gram of TNT, which builds up to about 4 grams per hour. True, the effect of a collision with microparticles or even atoms flying with

almost the speed of light is substantially different from that of a common explosion. In the latter case the metal surface is simply eroded, in the former different kinds of radiation develop, notably X-ray and gamma radiation, and a smaller portion of the energy is spent on the erosion of the "umbrella".

In the explosion of 1 gram of TNT, about 1 gram of metal is destroyed. Insofar as in collisions with particles flying at cosmic speeds most of the energy turns into radiation, with only about 0.1 per cent contributing to the destruction, the surface of the "umbrella" will erode at a rate of about 0.004 gram per hour, which is one gram in 10 days. The erosion can be further reduced by making the "umbrella" out of several layers of lead foil. The rate of erosion in this case is estimated to be no more than 10 grams of sheeting per square centimetre of surface per year. If the spaceship is accelerated very close to the speed of light the surface of the shield will start to glow. The radiation will be so powerful that it will vapourize oncoming material particles at a distance.

Nevertheless, a large meteoroid could pierce the "umbrella" and retain most of its velocity and mass. The impact, too, will be appreciable. To meet such an exigency the spaceship must be equipped with radar beacons. Electronic computers coupled with them will instantaneously calculate the direction of flight of the meteoroid and the chances of it hitting the ship. If their courses intersect, a ray gun emitting a powerful flux of high-frequency radiation will turn the meteor into a harmless cloud of dust and gas.

Here is another kind of hazard which future astronauts will have to reckon with. As a result of the action of cosmic X-ray radiation permeating outer space the spaceship will become positively charged. The impacts of particles and electromagnetic quanta eject electrons from the surface, disturbing the electromagnetic balance of the huge metal body. This will have no effect on the astronauts, and the unbalance can be observed only by delicate instruments. However, the electromagnetic fields of outer space will interact with the charged spaceship passing through them and retard its speed. Small as the

intensity of the electromagnetic field is at great distances from the gas and dust nebulae responsible for it, it acts continuously, day in and day out, week after week and month after month. Gradually the deceleration caused by it builds up to an appreciable magnitude.

Incidentally, a reversal of the effect, in which the ship would be accelerated, would hardly be much better, as it might accelerate so much that the available fuel would be insufficient for deceleration.

In the distant future, when astronauts will have explored interstellar space as thoroughly as seamen have explored the seas and oceans of our planet, the electromagnetic and gravitational fields of the Milky Way will be charted. Then the cosmic navigators will be able to exploit their accelerating or retarding forces. The charge of the outer shell of the spaceship can be neutralized by connecting it with the negative pole of a dynamo. Or it can be deliberately given a negative charge so that the electromagnetic field would act as an accelerator, thus compensating for the original retardation.

Many will be the hazards lying in store for the first astronauts on their twelve-and-a-half years' flight to Proxima. But the day will finally come when the star will start expanding into a visible disk. This will mean that it is time to slow down the ship. Once again the radiation motors will work steadily for 123 days. The rotation of the doughnut-shaped dwelling quarters, which provided synthetic gravity, will be stopped. The astronomers will start looking for the planets of Proxima, the mechanics will prepare the interplanetary ships for exploring and landing on them. The navigators will calculate the orbit in which the spaceship will circle Proxima as an artificial planet, the physicists will start exploring their first star "within reach" since the sun.

But let us leave the crew of our spaceship to their chores and hasten to earth so as to be there on the day when the first astronaut returns from his trip to another star.

One day in September 1522, a ship cast anchor at the Spanish port of San Lucar. Its battered hull, patched sails and the blackened boards of its deck all bespoke of a long and difficult journey. The gangplank had hardly touched the pier when a bearded man hastened down it, knelt and kissed the ground. He was Sebastian del Cano, head of the first expedition to circumnavigate the globe. Three years earlier a flotilla of five ships manned by a total crew of 265 had weighed anchor at that very pier. Only 18 men returned. Among those who did not come back was Ferdinand Magellan, the initial head of the expedition, who saw it through the most difficult part.

Soon the survivers of Magellan's expedition were called to task by the Catholic Church: for some strange reason their calendar proved to be short of one day as compared with that of their compatriots at home. This meant that they had observed the Catholic holidays on the wrong days, and the Church dealt severely with those who violated any of its canons. Scientists, however, soon explained the "loss" of one day. As they had circled the globe from west to east, trailing the sun, the travellers had, as it were, turned the earth one day back. Had they sailed eastwards they would have gained a day. Today this is

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Mathematically speaking

SOME RELATIONSHIPS OF SPECIAL RELATIVITY

The special theory of relativity postulates that all physical laws are the same in all coordinate systems moving uniformly in a straight line relative to one another (so-called inertial systems) and that the speed of light is always the same in any inertial reference system.

An important corollary of the relativity theory is the connection between mass and energy: mass is energy, and energy possesses mass. In the relativity theory the laws of conservation of mass and energy are superseded by a single law of conservation of mass-energy.

In classical mechanics, when a reference system O' moves with a velocity v relative to another system O along the x axis, the following simple transformations hold good:

accounted for by the International Date Line which passes from Pole to Pole down the Pacific Ocean. Anyone crossing it must either skip a day into tomorrow or turn back a day into yesterday.

Our question now is: will the calendar on earth coincide with the one kept by the astronauts in their trip to a neighbouring star?

The people of the earth are preparing to meet the travellers from outer space. Flower-bedecked stands surrounding the astrodrome are packed to capacity. A shattering roar descends from the sky. The operators at the landing guidance systems spring to attention. No, this is not the stellar ship itself. On earth it would collapse under its own weight and it has been placed in an elliptical orbit around the earth. Its crew comes down in a special rocket for interplanetary flight: there it comes into sight, preceded by a brilliant jet of flame cutting through the air. In a few moments it comes to a halt on the ground. A light aluminium ladder is wheeled up to the hatch. A grey-haired man in the tightly fitting suit of an astronaut appears on the platform. He was 27 when he left the earth on this journey. The journey back and forth took 25 years according to the terrestrial calendar, plus five years on the world of the distant star. How old is the man now? Fifty seven?

$$x = x' + vt', y = y', z = z', t = t'$$

where x, y, z, and t are the coordinates and time in the stationary system, and x', y', z' and t' are the coordinates and time in the moving system. If the velocity of a body in the primed system is u', in the unprimed system its velocity will be $u = u' + v$. The time is the same in both systems. These are the classical Galilean coordinate transformations.

The earth circles the sun at a speed of 30 km/sec, which is 1/10,000th the speed of light. It would appear that if scientists undertook to measure the speed of light coming from a star directly in front of the earth, when the earth's velocity is added to the velocity of light, and coming from a star directly behind, when the earth's velocity is subtracted from the velocity of light, they would detect a difference of 60 km/sec, large enough to be measured with the help of precise instruments. It was found, however, that whatever direction the speed of light

The astronaut descends to the ground and, like Sebastian del Cano five hundred years before him, kneels and kisses the stone surface of the astrodrome. His younger brother comes up to great him. But the younger brother looks much older and the astronaut concedes his seniority.

"When we took off," he says, "I was four years older than you. Now you are ten years my senior, for according to the clock of our spaceship I have lived only 16 years in the earth's 30 years."

A paradox? Yes, but neither the brothers nor the people around them wonder at it. It has been well studied. Long before the expedition to Proxima scientists had calculated the passage of time according to terrestrial clocks and the clock in the ship. But for us to understand this paradox we must return to the days when the scientists were first confronted by it.

In the middle of the 19th century, scientists considered that electromagnetic fields, and light in particular, were transmitted by vibrations of the ether, a very remarkable substance pervading the whole of the universe. All attempts to isolate this substance or detect any observable property of it invariably failed. All the scientists knew was that it was absolutely elastic and did not absorb light. Would it not be possible, they asked, to detect an "ether wind"? Could not one determine the direction in which a light source is moving by determining the

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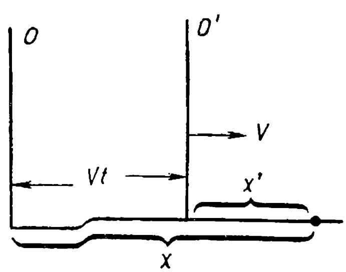
is measured in it is always the same. Albert Einstein suggested that the laws of velocity composition in classical mechanics, and hence the basic laws of classical mechanics, are inapplicable to velocities approaching that of light. Hendrik Lorentz, and later Einstein in simpler and more convincing form, developed new mechanical relationships. According to the new theory taking into account the aforementioned postulates, the



velocity with which the light from it propagates in different directions?

We have mentioned before that there is no difficulty in determining the direction in which a sound source is moving and if it moves faster than the speed of sound one simply doesn't hear it approach. What about light? Does it obey these laws?

In 1881, one of the greatest experimenters of all times, the American physicist Albert Michelson, carried out an experiment aimed at determining the effect of the motion of a light source on the propagation of light. Light travels extremely fast, and Michelson had to find a body which would be moving with sufficient speed relative to the luminiferous (or light-carrying) ether. The earth, which covers 30 kilometres per second in its motion around the sun, proved to be a suitable body. In fact, the accuracy of Michelson's instrument (called an interferometer) was such that even had the earth been making only 1.5 km/sec relative to the ether he could nevertheless have detected the "ether wind".

Michelson repeated his experiment several times, it was verified by others, but the result remained the same: no "ether wind" could be detected. The paradoxical implication of this discovery was that the velocity of light does not depend on the velocity of its source. But in that case some truly fantastic things become possible.

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coordinate and velocity transformations, known as the Lorentz transformations, are:

$$x = \frac{x' + vt'}{\sqrt{1 - \frac{v^2}{c^2}}};$$

$$t = \frac{t' + \frac{v}{c^2}x}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$y = y'; \quad z = z'$$

and

$$u = \frac{u' + v}{1 + \frac{u'y}{c^2}}$$

where c is the velocity of light.

The passage of time, it will be observed, is different in different reference systems, i.e., time is not an absolute quantity as was once assumed. If $v \ll c$, the Lorentz transformations turn into the classical Galilean transformations.

It will be observed that according to the new formula of

Imagine a train rushing past a station at a speed of 240,000 kilometres per second. Imagine further that the length of this train is commensurable with its speed, and it is 300,000 kilometres long. Such a train, which Lev Landau calls an Einstein train, would, of course, wrap around the world several times, but it suits our purpose admirably. Now suppose that just as the train approaches the stationmaster standing on the platform a light goes on at the front wall of the first carriage. We find that the effect of this simple action will be different from the point of view of the passengers and the stationmaster. The passengers will see the back wall of the last carriage light up in exactly one second's time. The stationmaster will see the back wall approaching the beam of light. A simple calculation enables him to say that the light falls on the wall in just over half a second. And both he and the passengers are right.

The inference is that, from the point of view of the stationmaster, time is passing slower inside the train than on the platform. If the Einstein train continues at its same speed through the universe and later passes by the platform again the passengers comparing their watches with the station clock will discover to their amazement that less time has passed in the moving train than at the motionless station. The words, "less time has passed in the moving train than at the motionless station", should be understood in the sense that the hands of a

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velocity composition the sum of two velocities can never exceed the velocity of light, no matter how close each velocity approaches that of light. In particular, the formula shows that if $u'=c$, $u=c$ irrespective of v. Thus the law of velocity composition satisfies the postulate of the constancy of the speed of light in any inertial frame of reference. The velocity of light is the maximum possible velocity in nature.

Some interesting corollaries can be derived from the Lorentz transformations. We shall consider only two of them.

Suppose we are moving together with the origin of a coordinate system O' at a velocity v relative to a coordinate system O attached to the earth. We measure the time t' with our clock, and the time t is measured in the system O on earth. As $x'=0$, the connection between the two times takes the form

clock in the train have circled the dial less times than the hands of the station clock, and that the passengers have aged less than the people on the platform.

Why don't we observe the phenomenon in everyday life? Why doesn't a ride to work make a man younger than the one who walks? The reason is that the dependence of the passage of time on the velocity of motion (which is known as time dilation) becomes observable only at very high, so-called relativistic, velocities approaching the speed of light.

The foregoing is one of the simplified corollaries of Einstein's special theory of relativity. Einstein published his theory in practically complete form in 1905, when he was only twenty six. Today it has been confirmed experimentally. Cosmic rays bombard the earth in a steady stream of particles of different kind. Their collisions with the nuclei of atoms in the atmosphere produce, among others, particles called mesons and hyperons. These are very unstable particles, and they decay in vanishingly short time into other elementary particles. Their lifetime has been measured with great accuracy and it is not enough for them to travel very far. Nevertheless, some mesons and hyperons reach the surface of the earth. Their lifetime is much longer than that of particles observed in laboratory conditions. The reason is that their velocity approaches the speed of light. A clock

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$$t' = t\sqrt{1-\frac{v^2}{c^2}}$$

We observe that according to our clock less time has passed than according to the terrestrial clock (the time paradox). Let us measure the length of a rod lying at rest in the O system along the x axis. In the primed system the coordinates of the ends of the rod are x'_1 and x'_2. Evidently,

$$x'_2 - x'_1 = (x_2 - x_1)\sqrt{1-\frac{v^2}{c^2}}$$

The length of the rod in our reference system is

$$l' = x'_2 - x'_1$$

In the terrestrial reference system the length of the rod is

$$l = x_2 - x_1$$

Hence,

$$l' = l\sqrt{1-\frac{v^2}{c^2}}$$

and the rod appears to have contracted. If we pass along the rod with the velocity v, or, what is the same thing, if

travelling with such a particle would show that its lifetime is just as long as it should be, neither more nor less. But, due to time dilation, the particle's "proper" time appears to be much slower from the point of view of a stationary observer, more time appears to have passed, and the particle covers a large distance.

Artificial earth satellites are comparatively fast-moving bodies. True, their speed—about 8 km/sec—is very small in comparison with the speed of light and the time dilation is insignificant. Still, it can be measured. The Soviet scientist V. Ginsburg suggests that a very accurate clock be placed in an artificial earth satellite and that its readings be compared with a clock on the ground in, say, one year's time. The predicted accumulation of 1/100th of a second difference would represent a new triumph for special relativity.

Today not only scientists but engineers, too, apply the formulas of relativity theory in designing installations in which electrons, protons, neutrons and other elementary particles must travel with sublight speeds, otherwise their answers would be all wrong. In dealing with great speeds Newtonian mechanics is as useless as butterfly nets for catching bullets.

And that is why, after his trip to Proxima Centauri, the elder of two brothers has become the younger one.

Time is one of the most mysterious concepts with which man deals daily and constantly. Like space, it is a form

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the rod passes by us with that velocity, it appears contracted by the ratio $\sqrt{1-\frac{v^2}{c^2}}$

With the help of a series of transformations taking into account the Lorentz transformations we can demonstrate that if the mass of a stationary body (the rest mass) is m_0, the mass of the body in motion will be given by the formula

$$m = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}$$

When v is very small in comparison with c (i.e., $\frac{v}{c} \ll 1$)

$$mc^2 = m_0c^2\left(1+\frac{v^2}{2c^2}\right) = m_0c^2 + \frac{m_0v^2}{2}$$

The quantity $\frac{m_0v^2}{2} = E_k$ is

of existence of matter. Time does not exist outside of matter, and the passage of time is measured by changes in matter. If matter ever existed as states and fields unknown to us it is equally possible that the forms of its existence—space and time in our understanding—were also different.

The knowledge that the "proper" time of a moving body is dependent on the body's velocity has raised quite a few questions. The faster a body moves the slower the flow of time. Does this mean that for photons, the quanta of light which travel at the speed of light, time does not exist? For it works out that, according to "their" clocks, they cover interstellar and intergalactic distances instantaneously.

Scientists have penetrated into the heart of the atom and dissected matter into elementary particles. They have discovered the discrete, quantized structure of electromagnetic, and possibly gravitational, fields. Attempts are being made to "quantize" space itself. But what about time? Is there such a thing as a quantum of time, the smallest, indivisible particle of time? And in general, what is the essence, the physical mechanism of time?

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simply the kinetic energy of the body; the quantity $m_0c^2=E_0$ is called the rest energy; the quantity $mc^2=E$ is the total energy of a moving body. Thus,

$$E=\frac{E_0}{\sqrt{1-\frac{v^2}{c^2}}}$$

Einstein showed that the energy of a resting body is $E_0=m_0c^2$. In nuclear reactions a part of the mass Δm_0 of the reacting matter turns into energy according to the formula $\Delta E_0=\Delta m_0c^2$. For uranium U^{92}_{235}, for example, $\frac{\Delta m_0}{m_0}\approx 1/1{,}500$ (in thermonuclear reactions $\frac{\Delta m_0}{m_0}\approx 1/100$)

The momentum of a body

$$M=\frac{m_0v}{\sqrt{1-\frac{v^2}{c^2}}}=\frac{Ev}{c^2}$$

increases, at a given energy, as the body's velocity. For $v=c$, we obtain $M=\frac{E}{c}$, but the rest mass m_0 of the body must tend to zero. Photons, for example, have no rest mass, but they carry energy corresponding to a certain equivalent rest mass.

These are all questions which scientists have still to answer. They are only just beginning to probe the essence of time. One attempt in this direction is the "quantization" of time. Imagine interacting elementary particles located very close to one another. The interactions take place in a finite time, and the interval between two such interactions cannot be zero, though it can be very small indeed. The smallest interval between two successive interactions can be called a quantum of time. After the interaction time "stops" for them, as their states do not change, until a new interaction. Thus, the change in a particle's state, in particular its energy state, represents, in a sense, the "flow" of time, which is of a discrete, quantized nature.

Obviously, the quantum of time must be very small, at least no longer than 10^{-24} second. But, we must repeat, this is still largely unexplored ground.

Explosion

The complex formulas of gas and fluid dynamics find embodiment in the streamlined shapes of supersonic aircraft

GAS DYNAMICS

The atmosphere, that gaseous envelope surrounding the earth, is in constant turbulent motion. Although proverbially invisible, the air is, unfortunately, far from absolutely transparent. Ask an airman who must constantly sweep the horizon with his eyes while in flight, and he will tell you of clouds and mists when the airplane seems to be floating through milk and the wingtips cannot be seen from the cockpit. He will tell you that even on a clear day a blue haze covers the horizon and the sharpest eye is unable to pierce it.

Ask a physicist, and he will tell you that the atmosphere is opaque to many sections of the electromagnetic spectrum. Only visible light, infrared radiation and radio waves of certain lengths can pass through it.

The people least satisfied with the atmosphere's transparency are astronomers. They choose for their observa-

tories places where the air is especially thin and the sky especially clear. They lift their optical instruments to mountain tops to reduce the layer of air between the eyepiece and outer space as much as possible. Even so, the opacity of the atmosphere makes many interesting phenomena totally unobservable. The quivering of the air due to heating distorts planetary features as observed in telescopes. As often as not this happens on the very night when, for once in a decade or more, a planet has approached closest to the earth. Elaborate expeditions travel to remote parts of the globe to observe an eclipse of the sun, only to return without having made a simple photograph because of a chance cloud reducing to naught the work of many months.

Not only the earth's atmosphere is in the way of astronomers. Many muttered curses have been addressed to the giant clouds of gas and dust obscuring vast portions of the Milky Way. The centre of the Milky Way, which is a dense, tightly packed cluster of stars, cannot be observed because it lies behind such a cloud. Only infrared radiation, with its greater penetrating ability than the rays of the visible spectrum, have enabled astronomers to photograph the bright Galactic nucleus whose gravitational pull controls the motions of millions of stars, the sun included.

The giant clouds of dust and gas are themselves interesting objects of exploration. Scientists want to know their composition, size, density, the gravitational and electromagnetic fields they generate and their common and reciprocal motions. The motion of interstellar matter can offer a clue to the forces which cause it, the composition and structure of cosmic formations and many other mysteries of the universe.

Fluid motion can be described as steady or unsteady. Suppose an investigator is studying the flow of gas through a main. He measures the temperature, velocity and pressure at different points across the stream. He carries out the same measurements every ten minutes for some time and finds that the readings of his instruments remain the same, that is to say, the flow parameters do not change with time. This is the case of steady flow.

If the investigator continued his experiments he would find that at night the velocity of flow is somewhat smaller than in daytime, that in winter the fluid is colder than in summer. As these fluctuations are periodic the motion is described as quasisteady.

In studying the motion of gases in the firing of a cannon or the explosion of a shell we find that the pressure, temperature, speed and direction of the moving gases are constantly changing. This is an example of unsteady or turbulent motion, and this is the kind of motion observed in cosmic clouds of dust and gas.

During our tour of the universe we found that most of the matter of which it consists is in a plasmic state. The mass of our "plasmic" sun is 750 times the total mass of all its attendant planets. In the Milky Way the percentage of plasma is even greater as, besides the stars which constitute the bulk of the Galaxy, the intragalactic gaseous nebulae and the extremely rarefied interstellar medium are also constituted of plasma. The solid and, especially, liquid states of matter are rare indeed on a galactic scale. Solid matter is found, besides planets, comet heads and meteoroids, in the extensive dark nebulae which represent agglomerations of cosmic dust. Finally, there may possibly exist cooled stars encased in hard crusts, although no direct observations of such objects

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Mathematically speaking

RIEMANN'S EQUATION

In the case of unsteady flow (i.e., flow dependent on time) the connection between the velocity, density and pressure of the fluid is given by Riemann's equation:

$$u = \pm \frac{2}{k-1}\sqrt{\frac{kp}{\rho}} + \text{const} = \pm \frac{2}{k-1} a + \text{const}$$

where a is the velocity of sound, ρ is the density of the fluid, p is the pressure, and k a coefficient of proportionality.

In the case of a fluid flowing out of a vessel the minus sign is taken, as the pressure decreases, the velocity increases, and

$$u = \frac{2}{k-1}(a_0 - a),$$

where a_0 is the velocity of sound in the resting fluid.

have yet been made. In short, solid matter accounts for hardly one-tenth of one per cent of the Galaxy, and liquid matter probably accounts for less than a millionth of the total mass.

As everything in the universe, cosmic gases are in constant motion. In a few rare cases, as in the tails of comets, the motion is relatively steady. In other cases, such as the outburst of a "new" star, the ejection of gases is of an explosive nature. And this brings us from the realm of astronomy to gas dynamics, the science that treats of the laws of motion of compressible fluids. The concept of fluid, it should be borne in mind, embraces plasmas, gases, liquids, and even solids, if the pressure is high enough (as mentioned before, at high pressures solids begin to behave like liquids). Gas dynamics is a rapidly progressing division of physics. Its laws and conclusions have proved useful not only for "pure" theory but also for such practical applications as nuclear engineering and rocketry. It is to be regretted that astronomers disregard many theoretical conclusions of gas dynamics. More than a century has passed since Kant's and Laplace's classical researches in the cosmogony of the solar system. Their hypotheses were based on the methods of gas dynamics, but since then astronomers have all but forgotten the science. Only in the last few years has interest in it begun to awaken.

In the case of steady flow of a gas into vacuum, where $a=0$, the limiting speed of outflow of the gas is

$$\bar{u}_{lim} = \sqrt{\frac{2}{k-1}}\, a_0$$

In the case of unsteady outflow the velocity of the gas is

$$u_{lim} = \frac{2}{k-1}\, a_0$$

The ratio of the velocities is

$$\frac{u_{lim}}{\bar{u}_{lim}} = \sqrt{\frac{2}{k-1}}$$

which gives for air, where $k=\frac{7}{5}$, $\frac{u_{lim}}{\bar{u}_{lim}} = \sqrt{5} \approx 2.25$

It thus appears that the limiting velocity of a gas in unsteady flow in the formation of a rarefaction wave, in the case of a large pressure drop, is greater than for the same pressure drop

The gas dynamics of outer space differs markedly from "terrestrial" gas dynamics. It is infinitely more complex, and this is due not only to the grander scale it involves. Matter in the universe is largely in a plasmic state. Its motion is affected by forces generated within the plasma itself as well as by the action of gravitational and electromagnetic fields. At velocities approaching the speed of light the mass of matter changes together with the flow of time. Obviously, cosmic gas dynamics is still largely a terra incognita. But let us examine some of the initial conclusions and ideas that have recently emerged.

GAS FLOW INTO VACUUM

A supernova is a very rare event, and in the whole of the Milky Way it happens on an average of once every two or three hundred years. One understands therefore why astronomers are so excited when they see that a tiny bright speck on their photographic plates has begun to expand at the rate of a fraction of a millimetre a day. Other research methods also bring an information about the cataclysmic catastrophe enveloping the distant star. Spectroscopes display an almost continuous spectrum in which broad bright bands soon appear. Not all of them can be identified with the spectral lines of known chemical

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in steady flow. This, however, is the case only at the front of an unsteady stream, and farther back the velocity is less than $\overline{u}_{lim}$

When a gas is compressed by a piston whose velocity is gradually changing, as the pressure increases with the velocity,

$$u = \frac{2}{k-1}(a - a_0)$$

It follows from this that

$$a = a_0 + \frac{k-1}{2} u$$

and that the pressure of the gas

$$p = p_0 \left(\frac{a}{a_0}\right)^{\frac{2k}{k-1}} = \left(1 + \frac{k-1}{2}\frac{u}{a_0}\right)^{\frac{2k}{k-1}}$$

In the expansion of a spherical volume of gas in vacuum, the

elements. Radio telescopes detect a new powerful source of radio signals which may even "outshine" the sun.

The term "supernova" should not be understood to mean that the star is really "super-new". Before it flared up it was a small and insignificant star which had not even been studied spectroscopically to determine the relative abundance of chemical elements in it. Now it has exploded, spewing vast quantities of plasma into outer space at speeds of 5,000-10,000 kilometres per second. This fast motion explains the broadening of the spectral lines. The actual motion of the cloud of plasma, fast and turbulent as it is, is not apparent from the distance of the earth.

The powerful radio signals coming from the supernova are not cries of help from intelligent beings which may have populated one of its attendant planets. For them all would have been over much earlier. The signals are emitted by electrons travelling with almost the speed of light which are slowed down by the electromagnetic field.

Several weeks will pass, the star's brightness will gradually decrease, and in time it will become the little old star it was, only surrounded by a nebula of its own making. Several such nebulae have been identified with novae and supernovae. One of the best known is the so-called Crab Nebula, which is the remnant of the explosion of a supernova in 1054. The fact of the explosion was recorded by contemporary Chinese astronomers. And a simple calculation based on the known speed with which

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velocity of expansion will also be

$$u_{lim} = \frac{2}{k-1} a_0$$

When the radius of the sphere increases to 10-15 times that of the initial radius, the velocity of the gas will be described by the equation

$$u = \frac{r}{t}$$

where r is the distance from the centre, and t is the time from the beginning of the process. At any given time the velocity of any particle of the gas is in direct proportion to its distance from the centre of the explosion. The density of the gas is the highest at the centre of the explosion and drops sharply towards the periphery.

the nebula is expanding yields the date when it was concentrated at a point.

An explosion is a sudden outburst in which large quantities of energy are emitted. Thus, in the explosion which produced the Crab Nebula, 10^{49} ergs of energy was emitted. The outburst of a supernova, a lightning bolt or the instantaneous combustion of dynamite in a blasting cartridge are all explosions of different types. But before discussing the laws of motion of gases and plasma in explosions an introductory discourse is called for.

Gas is compressible. If this needs confirmation one can prove it with the help of an ordinary pump for inflating a flat tyre. In some cases the density of a gas changes insignificantly and its compressibility can be neglected. Thus, in calculating the wing of a subsonic aircraft engineers do not take into account the compressibility of the air, and it is assumed to be a noncompressible fluid. The resulting deviation of the calculated from the actual lift is insignificant. This is a case of steady flow of air.

If we begin to study the propagation of sound we must of necessity consider the changes that take place in the pressure and density of the air, which can no longer be likened to a noncompressible fluid. In general, at velocities of gas approaching and higher than the speed of sound, compressibility must be taken into account even in cases of steady flow.

Imagine the following simple case of unsteady gas flow. A closed pipe is divided into two parts, one containing a greatly compressed gas, the other, a vacuum. The abrupt removal of the dividing wall causes something of an explosion. The gas particles adjacent to the wall are pushed by the particles behind them out into the evacuated end of the pipe. The pressure, apparently, drops. The signal of this pressure drop (and the accompanying scattering of the particles) is transmitted to the particles which have not yet begun to scatter with the speed of sound. As soon as the signal reaches a new layer of particles they experience a pressure which is greater than the pressure in the particles before them, and they also begin to scatter. However, as the difference

between the pressures exerted by the particles in front and behind steadily decreases, the velocity of each successive shell of scattering particles is smaller and smaller. When the first shell began to scatter the pressure in front of it was zero, and its particles were subjected to a one-way pressure equal to the initial pressure. For each successive shell the pressure from behind remains the same, but in front there is a steadily increasing mass of gas. The gas is accelerated by the pressure difference, which is less than the initial pressure, hence the velocity is less.

When the signal travelling from the first layer of expanding gas back through the successive gas shells behind it (the rarefaction or suction wave) reaches the walled end of the pipe it is reflected and travels back again towards the main signal. The expansion of the gas will, obviously, continue, but the nature of its motion will change. Before its reflection the wave had been passing through a nonexpanding gas. Now it is propagating through a moving gas. It should be noted that whereas in the primary wave the pressure drops sharply in the direction from the wave front to the expanding edge, in the reflected wave the pressure is almost uniform over the volume of gas, though it decreases rapidly with time.

Before expansion the gas particles possessed potential energy, which was the same throughout the volume. After expansion most of the potential energy turns into kinetic energy and the pressure drops markedly. But different portions of the gas possess different kinetic energy. It is highest at the blast front and lowest (zero) in particles adjacent to the wall. It needs no computations to conclude from the above reasoning that the velocity of the front particles is greater than the average velocity as determined from the simple law of conservation of energy. Something similar is observed in the recoil of a compressed spring having one end fixed. The energy of the fixed end is nil while that of the free end is greater than average. Another analogy can be seen in the "ejection" of passengers from a packed subway train. The people in the car push one another like the molecules of gas. When the pneumatic doors slide open at a station the

people next to them are literally shot out, while those behind them crowd through in the doorway and the velocity of flow decreases as in the case of a gas.

Let us investigate the motion of gas in a pipe when it flows not into a vacuum, but into a region filled with a gas at lower pressure. Theory and experience tell us that the outflowing gas expands and its pressure decreases. The pressure of the invaded gas increases until the two balance. In this case a shock wave generates at the moment when the expansion begins. It is an interesting phenomenon which must be examined before we can get an understanding of the mechanism of explosion.

SHOCK WAVES

Shock waves are observed in a variety of natural phenomena. Their applications for human needs are unfortunately restricted largely to military use. A lightning bolt is followed by a thunderclap, which is the propagation of a shock wave through air. The flight of a shell, a supersonic aircraft, in fact, any motion through gas faster than the speed of sound produces a shock wave, also known as a ballistic wave, a blast wave and, in supersonic air flight, a sonic boom.

In the explosion of a shell or bomb the blast wave propagates in all directions. Powerful blast waves are produced in the explosion of atom and hydrogen bombs. But the greatest shock waves of all are generated in outbursts of novae and supernovae, some of the most awesome sights in nature.

Although explosion phenomena, to say nothing of thunderclaps, have been known to man for centuries, the discovery of shock waves and their investigation as a physical phenomenon dates back no more than a hundred years or so. The existence of shock waves was first predicted theoretically in the late 1850s by the great German mathematician Bernhard Riemann. One could say that shock waves were discovered for science like the planets Neptune and Pluto, "at penpoint".

In 1870 the English scientist Samuel Earnshaw arrived at similar conclusions through a different course of reasoning. A substantial contribution to the study of shock waves and their physical interpretation was made in the late 1880s by the French scientist Hugoniot. At about the same time Ernst Mach, the Austrian physicist and philosopher, first produced shock waves in an experimental setup. For a long time, however, scientists took only a casual interest in shock waves as they appeared to have no practical applications.

Theoretical interest in the phenomenon began to revive only late in the 1920s, when it became apparent that the progress of aviation would eventually lead into the supersonic domain. The flight of artillery projectiles, which were already travelling at supersonic speeds, was studied in great detail. But the study of shock waves in real earnest began only during the last world war. The advance of science and technology insistently demanded a comprehensive study of waves in both the theoretical and experimental aspects. Hundreds of scientists in many countries are studying them today, and the science of shock waves has now become a comprehensively elaborated chapter of modern physics. In the Soviet Union substantial contributions to it have been made by Lev Landau, L. I. Sedov, Y. B. Zeldovich and A. S. Kompaneyets.

In a compressible medium any disturbances, such as a change in pressure at some point, propagate with the speed of sound. In fact, the speed of sound can be defined as the speed with which a disturbance is transmitted through a gas. For the sake of simplicity, we shall speak only of gases, although shock waves can be produced in plasmas, liquids and solids. The speed of sound in a gas or plasma varies directly as their density, and for air at 0°C and 760 mm of mercury it is 340 metres per second.

The mechanism of a shock wave is as follows. Imagine a very long pipe with a piston moving in it at one end. It compresses the gas, creating a local increase in pressure and density. This disturbance propagates along the pipe with the speed of sound. If the piston is made to move

faster, an additional compression of the already compressed portions of the gas takes place. The new perturbation also travels with the speed of sound which, however, will now be greater as it is passing through denser gas. A further increase in the piston's speed compresses the already twice compressed portions of gas. The new pressure and density travel away, once more with the speed of sound, which is again higher. In this way the successive pressure disturbances will overtake the ones before them until at some point along the pipe all of them will catch up with the initial disturbance. What happens then?

A jump develops in the density, pressure and, consequently, temperature of the gas. At the far end of the pipe the gas is at its initial density and pressure; behind the jump they are greater. This jump is a narrow region no thicker than several free runs of a molecule, which is the distance necessary for the molecules to exchange their energies, and it is called the shock wave or detonation front. Thus, the shock wave travels through the gas faster than the speed of sound in the undisturbed, uncompressed gas. The velocity of the shock wave is the greater the faster the piston moves and the greater the compression of the gas in front of it. The shock wave forms the faster the greater the acceleration of the piston. If the velocity gradient is very steep the shock wave forms at once.

Mathematically Speaking

SHOCK WAVES

If a gas is compressed by a piston which starts at once, with a jerk, to move with a velocity v, a shock wave will travel through the gas with a speed

$$u = \frac{k+1}{4} v + \sqrt{\left(\frac{k+1}{4} v\right)^2 + a^2}$$

where a is the speed of sound. (When the velocity of the piston is not great, and $v \ll a$, we obtain that the shock front propagates with the speed of sound, a.)

The pressure and density of the gas are given by the equations

$$p = p_0 + \rho_0 v^2 \left[\frac{k+1}{4} + \sqrt{\left(\frac{k+1}{4}\right)^2 + \frac{a^2}{v^2}} \right]$$

$$\rho = \rho_0 \frac{(k+1)p + (k-1)p_0}{(k-1)p + (k+1)p_0}$$

A shock wave also forms in the impact of a gas jet on an obstacle, and it travels back along the jet. In this case the obstacle acts as the piston. The impinging particles slow down and come to a halt. The jet need not be moving with supersonic speed.

The velocity of the shock wave, like the velocity of propagation of the disturbance, must not be confused with the velocity of the gas flow. As a shock wave passes through a gas the pressure, density and temperature increase. The heating in a shock wave is much greater than in ordinary compression.

Dispensing now with our pipe, if the piston moves not very fastly through the air, the air will merely flow by it and the compressions formed will spread in all directions without creating a shock wave. But when the "piston" attains the speed of sound (and becomes an artillery shell) the picture changes markedly. The pressure disturbance, which travels with the speed of sound, can no longer overtake the supersonic shell. A pressure jump develops in front of the shell which is separated from the undisturbed gas by a shock wave. Only now the shock wave is not flat as in the pipe, where its front was perpendicular to the motion, but at an angle to the shell. High-speed cameras produce some very beautiful pictures of the flight of a projectile through air in which shock

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where p_0 and ρ_0 are the initial pressure and density, respectively, of the stationary medium.

In the case of a powerful shock wave, when $p \gg p_0$, the equations become much simpler:

$$u = \frac{k+1}{2} v$$

$$p = \frac{k+1}{2} \rho_0 v^2$$

$$\frac{\rho}{\rho_0} = \frac{k+1}{k-1}$$

The temperature

$$T = T_0 \frac{k-1}{k+1} \frac{p}{p_0}$$

where T_0 is the initial temperature.

For air we have:

$$u = \frac{6}{5} v; \quad p = \frac{6}{5} \rho_0 v^2$$

$$\frac{\rho}{\rho_0} = 6; \quad \frac{T}{T_0} = \frac{p}{6p_0}$$

It should be noted that the density at the front of a powerful shock wave is constant and that the temperature increases

waves are seen to spread in a cone from the nose. A similar picture develops in the flight of a supersonic aircraft. An observer on the ground first hears the sonic boom generated by the shock wave and only then does he hear the sound of the engine.

The physical laws governing the behaviour of flat, conical, cylindrical or spherical shock waves are the same. Their main feature is a sharp increase in pressure and temperature, which may even rise hundreds and thousands of times. In laboratories shock waves are used to develop superhigh temperatures. A suitable installation is a steel oblong or round pipe 10 centimetres thick and several metres long. A diaphragm separates the high-pressure from the low-pressure side. In the former the pressure is around 100 atmospheres, in the latter it is usually several hundredths or even thousandths of an atmosphere. When the diaphragm is ruptured the high-pressure gas rushes into the low-pressure side and, like a piston, compresses the gas there. The pressure disturbance almost instantaneously turns into a shock wave which travels along the low-pressure chamber. The high-pressure working gas is usually hydrogen, which does not heat and only works as a piston. The low-pressure chamber is filled with a heavy gas, krypton, for example, through which the shock wave travels. At the point where the direct and reflected

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in proportion to the pressure, i.e., much sharper than in slow compression, when

$$\frac{T}{T_0} = \left(\frac{p}{p_0}\right)^{\frac{k-1}{k}}$$

which for air gives

$$\frac{T}{T_0} = \left(\frac{p}{p_0}\right)^{\frac{2}{7}}$$

For example, if $T_0 = 300°$ K and $P_0 = 1$ ata, then a compression to $p = 100$ ata will yield in the first case

$$T = \frac{300 \times 100}{6} = 5{,}000°\mathrm{K}$$

and in the second case,

$$T = 300 \times 100^{\frac{2}{7}} = 1{,}100°\mathrm{K}$$

and the temperature is lower by a factor of almost five.

In compressive impact more energy is dissipated as heat, and it does not contribute to increasing the density.

shock waves meet the temperature may rise to 25,000 degrees.

Much higher temperatures are attained in the explosion of an atom bomb, and even more so of a hydrogen bomb. At the initial stage, when the detonation front embraces a small volume, the temperature in the shock wave reaches several million degrees. But even these temperatures are by far surpassed by those generated in the shock waves produced by the outburst of a supernova.

EXPLODING STARS

Some day an observatory will report the outburst of a supernova in some remote part of the Milky Way. If one can speak of the simultaneity of events separated by such vast expanses, at the time of the explosion the people peering into the starry heavens were cavemen dressed in animal skins. Centuries and millennia rolled by. Man tamed animals and learned to till the soil. He created cultures and established states. Through subtle logical constructions philosophers came to an understanding of world structures. And still the dim little star twinkled unobtrusively in the sky and no one paid any attention to it. The age of cognition of the world came. Huge telescopes peered up into the sky. Delicate diffraction gratings resolved the weak beams of stellar light reaching the earth into their component parts, and no one paid attention to the little star. Only now, several tens of thousands of years after the catastrophe, telescopes are hastily turned towards the star to study the history of the awesome tragedy. In the explosion the star loses some 10 per cent of its total mass, and the light flux from it increases a hundred million times. What takes place in its hot bowels and the space around it?

It is a sure guess that the explosion is caused by nuclear reactions, probably involving both light and heavy elements. A supernova stays at its brightest for a day or so. This is about the same as the half-life of the heavy transuranium element of californium. Could it be the main cause of cosmic catastrophes, the explosive which

kindles the flame of a supernova? Or does deuterium provide the fuel? If the space around the star abounds in deuterium nuclei the star's powerful gravitational pull could draw them in. The resulting thermonuclear explosion produces the cataclysm. We can only hypothesize concerning the mechanism of the explosion. One possible sequence originates when the tremendous pressures and temperatures reaching tens of millions of degrees trigger thermonuclear and other reactions in the middle of the star. The enormous output of energy creates a shock wave which travels from the centre to the periphery. Although the star's density decreases rapidly towards the surface, the shock wave continues to accelerate regardless of the decreasing pressure at its front. Behind the front the temperature of the plasma is many tens of millions of degrees. The plasma moves in the same direction as the shock wave front, though somewhat slower. This slower speed is nevertheless probably hundreds, thousands and may be even tens of thousands of kilometres per second. Just as the shock wave leaves the stellar atmosphere it comes to sight. The brilliant flash of the shock wave, where the temperature is thousands of times greater than that of the star's surface, is the first signal informing the universe of the catastrophe.

As the masses of plasma following the shock wave are travelling at great speeds, some of them overcome the star's gravity and dissipate in outer space. The farther from the shock wave front and the closer to the centre, the less the velocities of the particles. At the centre the velocity is zero and the density is maximum. Therefore only a small portion of the star is accelerated to velocities sufficient to carry it away into outer space.

The bulk of the ejected matter slows down and then starts falling back. As it collapses into the middle of the star it produces a new expanding shock wave. This will happen even if no nuclear reactions take place to yield energy. In this case a new flash of almost the same intensity as the first one will be observed. Such pulsations accompanied by ejections of matter and brilliant outbursts will apparently continue until the star loses much of its mass and the temperature at its core falls too low

to sustain the powerful reactions in it. The period of such fluctuations may vary from anywhere between several hours and several millennia.

When the star subsides to a relatively small size it will begin to pulsate very uniformly. Such pulsating variables, as they are called, are known as the Cepheids. Their rhythm is as stable as clockwork. The Cepheids may represent the last stage in the development of stars, which began as supernovae and after hundreds and thousands of years developed into novae. It appears that a supernova explosion can happen to a star only once, and not many stars are destined to flare up to magnitudes that make them visible from other galaxies.

It is natural to ask whether the closest star we know, the sun, will ever explode in this manner. The sun is a practically inexhaustible source of energy. Great spurts of energy erupting to the surface cause the huge explosions which we observe in the solar atmosphere. Whereas in terrestrial conditions natural processes of an explosive nature (volcanic eruptions, for example) are comparatively rare, on the sun and in its atmosphere they take place continually. A classical example is the eruption of prominences.

Fifteen or twenty years ago the movement of prominences appeared to be simple and easily explainable. Huge clouds of glowing gas drift over the surface of the sun. Their weight is balanced by the pressure of light emitted from the blinding bright photosphere. These are quiescent prominences. Then some hot gases erupt just below a quiescent prominence, the light pressure increases sharply and the prominence shoots up like a fiery geyser. This was the picture that presented itself when people could photograph prominences only in the rare moments of total eclipses of the sun. Recent studies, however, reveal that the phenomenon is not so simple.

New techniques have made it possible to photograph prominences with moving-picture cameras at any time of the day. A thorough study of these films reveals that prominences do not necessarily move only upwards. They move in all directions, including downwards, towards the sun's surface. Characteristically, the hydrogen, gaseous calcium and other gas components follow trajectories

which resemble the lines of force of electrical or magnetic fields. There can be no doubt that along with solar gravitation and light pressure electromagnetic forces also play an important part in the formation of prominences.

Eruptive prominences account for only 10 per cent of the total observed. Their rapid outbursts, with velocities as high as 700 km/sec, are of the nature of explosions. The power of solar explosions can be judged from the fact that some prominences reach out to a height equal to the sun's diameter, more than a million kilometres. As a rule the lifetime of an eruptive prominence is about half an hour. As it reaches maximum height it falls apart into jets of gas which partially dissipate and partially collapse sunwards. A more detailed and precise theory of solar atmospheric phenomena is a thing for future astronomers.

Another solar mystery are the so-called flares, which occur continuously in the chromosphere. They are best observed in hydrogen emission light and have the appearance of explosions. Sometimes there can be observed a bright central nucleus which spews gleaming jets of gas in all directions with speeds of up to 300 km/sec. Some flares resemble underwater explosions. An intensely bright cloud rapidly spreads out like ink on a blotting paper. Soviet astronomers A. B. Severny and E. F. Shaposhnikova have associated many such phenomena with the development and disintegration of sunspots. On 10 May, 1950, Severny observed a flare from which there spurted an unusually brilliant jet of glowing hydrogen moving at a speed of 400 km/sec.

Processes on the sun affect terrestrial phenomena. Thus, a great flare on 23 February 1956 disrupted radio communication all over the world and possibly even affected the weather. During solar flares the flux of cosmic rays increases markedly. This is an indication that the flares may possibly be due to nuclear processes like those taking place in the explosion of a thermonuclear bomb. Not long ago the sun was for the first time photographed through a small telescope lifted aloft in a high-altitude rocket. The photographic film presented the sun's surface as it will be one day seen by astronomers from a lunar observa-

tory, without distortion by the terrestrial atmosphere. The picture revealed a surface bubbling with explosions the smallest of which would be capable of reducing the earth to ash; the earth would be as helpless in the stream of a large prominence ejected by a plasmic explosion as a splinter in a maelstrom.

Nevertheless, we need not fear that our sun will some day explode. The sun belongs to the category of quiet, stable stars. It is rather small and though it is not a very hot star, it will supply humanity with energy for billions of years to come without flaring up or going out. Man will have sufficient time to advance his culture to unimaginable heights, and long before the sun reaches a dangerous old age he will have penetrated into the greater Milky Way where he will be able to populate any number of planets in other stellar systems.

COSMIC CLOUDS

On a clear winter night one can see a dimly glowing spot in the constellation Orion. This is the Orion Nebula, one of the most interesting objects in the sky. It is a huge cloud of rarefied gas and plasma some 10 light years in diameter. The atoms of gas absorb the light of nearby hot stars and re-emit the absorbed energy as a cold, phosphorescent glow. The Orion Nebula has been studied by many astronomers. Some interesting data were obtained recently by F. G. Fesenkov of the Soviet Union in Alma-Ata.

What strikes the eye in the Orion Nebula is its complex structure: it appears to consist of eddies and jets of huge masses of gas in violent, turbulent motion. The Orion Nebula is some 500 light years away, which makes it impossible to observe the motion of the gases directly. It takes thousands of years before the pattern of turbulence can change sufficiently for us to observe it at the distance. Only displacements in spectral lines tell scientists that the gas is in motion, some jets travelling as fast as 7 km/sec. It stands to reason that other nebulae like that of Orion are in similar turbulent motion.

What causes the motions of gas and plasma in outer space? We have already mentioned that one of the forces responsible is the gravitational field attraction of neighbouring stars and the gravitational field of the Milky Way as a whole. Other agents include gas pressure and electromagnetic fields. The component particles of cosmic clouds, it should be remembered, are charged, and in their motion they generate electromagnetic fields with which they interact.

The outstanding investigations of G. A. Shain and other Soviet astronomers in recent years indicate beyond doubt that the structure of gas nebulae is largely determined by the action of electromagnetic forces. It even seems probable that the spiral structure of the Milky Way is also due to electromagnetic field action on a cosmic scale. Finally, it is also possible that in some cases the motion of nebulae may be affected by the pressure of light from nearby stars.

The forces which display themselves in the gaseous eddies of visible nebulae also act on the extremely rarefied gaseous and plasmic interstellar gas which pervades the Galaxy. The discovery of interstellar gas dates back to 1904, when absorption lines of interstellar calcium were discovered in the spectrum of the double star δ Orionis. At first it was thought that interstellar gas consisted exclusively of ionized atoms of calcium, but later atoms of sodium, titanium, iron and other elements were discovered, as well as some molecules of cyan (CN) and hydrocarbons. Interstellar gas has a vanishingly small density of 10^{-24} g/cm^2, which means that to every cubic centimetre of space there is only one molecule of gas. It is nevertheless a far from homogeneous medium and even in its tenuous structure there are condensations, rarefactions and huge whisps of turbulence which remain unobserved only because of their extreme rarefaction. The gas is in constant turbulent motion and in addition, as has been recently established, it takes part in the rotation of the Milky Way as a whole.

The origin of interstellar gas and gas nebulae remains unclear. Quite possibly, as B. A. Vorontsov-Velyaminov's researches indicate, the supply of interstellar gas comes

from stars. In addition to novae and supernovae, there are other types of stars which eject large quantities of gas into outer space. Neither can the possibility be ruled out that in some conditions ejected gases are capable of recondensing into brand new stars. This thesis is supported by V. G. Fesenkov, who finds a close connection between the configuration of the gaseous filaments in nebulae and linear assemblies of stars within them.

Thus, in some cases the motion of plasma may give rise to explosions of incredible force, in other cases it may lead to the creation of new stellar worlds.

Recent by explosions of such magnitude have been discovered which dwarf a supernova outburst as much as the sun dwarfs a burning match. A photograph of a galaxy in the constellation Virgo designated NGC 4486 presents a remarkable formation: a huge tail or filament extending from the galactic nucleus to the periphery. There are several knots on the filament, which is shooting outwards at a speed of some 300 km/sec. The filament was discovered in 1918, but only after NGC 4486 was identified as a powerful radio source was it associated with radio emission. A spectral analysis of the filament indicates that it is probably of plasmic nature. It may represent a powerful jet of gases out of the galactic nucleus. Free electrons in the jet could attain speeds close to that of light, thus causing the powerful radio emission. The jet may also be due to a tremendous explosion in which tens of millions of times more energy was released than in a supernova outburst. This makes it easily the greatest of all known explosions in nature. The only known energy source capable of such a yield is the collision of matter with antimatter. We can only conjecture as to how a huge cloud of antimatter could have penetrated into a galactic nucleus and how the explosion itself could have progressed.

Such jets, it now appears, are neither unique nor rare in the world of galaxies. V. A. Ambartsumyan, a leading Soviet astronomer, recently drew attention to several galaxies featuring jets and filaments which may well be due to explosions greater than the one taking place in NGC 4486.

It has also been suggested, however, that the protruding filaments may not be due to explosions. We have mentioned before that the movement of matter in nebulae, as well as their shapes and interactions, cannot be explained by gravitational forces alone and that forces of an electromagnetic nature must surely be acting between them. Gravitational forces decrease as the square of the distance. In a conducting medium such as outer space electrical fields are practically nonexistent, but magnetic fields are present. A magnetic field possesses axial symmetry and therefore it weakens with distance slower than a gravitational field, the decrease in intensity varying directly as the distance. Hence, over certain distances interactions of galactic magnetic fields may be much greater than gravitational interactions and the slow, steady action of the magnetic fields may well prove to be the cause of the observed huge plasmic jets. It will take time to answer these questions. Meanwhile the study of these remarkable facts is an exciting task for both astrophysics and the gas-dynamic theory of explosions.

SPEED AS AN EXPLOSIVE

By "explosion" is meant a practically instantaneous transformation of energy from one form into another, for instance, chemical into heat, as in the explosion of TNT, or electrical into heat, as in a lightning bolt. Whatever the cause, the hidden, latent, "passive" energy suddenly manifests itself in streams of radiation, claps of thunder or ejections of plasma.

But there is another kind of explosion, in which the kinetic energy of motion is converted into heat. A simple calculation reveals that if a body moving with a speed of four or five kilometres per second is instantaneously halted it will explode as though it were made of a high explosive. The destruction that can be caused by a big meteor, which may have speeds of 30, 40 and even 70 km/sec, is comparable with that caused by a nuclear explosion. The earth carries many scars as tokens of collisions with such explosive material. The biggest known

meteorite crater, in Labrador, is three kilometres in diameter. The famous meteorite crater in Arizona measures 1,200 metres across and 175 metres deep. Smaller craters have been identified in many parts of the world. They resemble shell holes in shape and also in the way they were formed.

A meteorite weighing several tens or hundreds of tons entering the atmosphere at a speed of several kilometres or tens of kilometres per second carries tremendous kinetic energy. The resistance of the atmosphere is unable to reduce this energy appreciably and the meteorite hits the ground at practically its initial cosmic speed. The impact generates shock waves which propagate from the point of impact through the meteorite and the ground. If the velocity of impact is above a certain limit the pressure at the shock front may be so high that the molecules and atoms of the crystal lattice are pushed very close to each other. Forces of repulsion come into play, and when the shock wave passes we will have instead of a solid body one in which all the crystal bonds have been destroyed, a gaseous body, in fact. This will be a new, enormously compressed gas, as it occupies the initial volume of the solid body. Being a gas it will start to expand in all directions, pushing aside the containing medium—exploding, in other words.

On 30 June, 1908, a huge fiery body hurtled from south to north over the Siberian taiga forest. It hit the ground somewhere in the vicinity of a river called the Podkamennaya Tunguska with a bang that has rarely been rivaled in the whole of the earth's history. The seismic wave ran all around the globe and the blast was heard a thousand kilometres away. Unfortunately, old Russia lacked the facilities to study this remarkable phenomenon. Only after the Socialist Revolution of 1917 did the first expedition, headed by L. A. Kulik, visit the site. What he saw at the epicentre of the explosion was remarkable indeed. For instead of the expected giant crater he found charred standing trees stripped of their branches. Kulik explored the site of the Tunguska meteorite several times and he was unable to find a single piece of meteorite matter. The 1941-45 war halted the exploration of the unique phe-

nomenon of nature for many years. The next expedition, headed by the young scientist K. P. Florensky, came only in 1958. After a thorough study of the site the scientists came to the conclusion that the blast must have taken place in the air. How could this be? After all, the meteorite could hardly be made up of an explosive.

A clue to the answer may be provided by an investigation of the circumstances of the fall of the Sikhote-Alin meteorite in Siberia in 1947, which was carefully studied. It was an iron meteorite which overtook the earth in its motion and entered the atmosphere at a speed of approximately 12 km/sec. At an altitude of 12-14 kilometres, where the density of the air increases sharply at the boundary of the stratosphere and the troposphere, the retardation of the meteorite was so great that the shock wave broke it up into several score big and a great number of small fragments. A study of the debris revealed that the structure of the meteorite was conducive to its breaking up. In addition, the breaking up of a meteorite in the air is further facilitated by its rotation. Meteorites are irregular shapes and, depending on the surface they turn forward, shock waves of different kinds will pass through their bodies. The fragments of the Sikhote-Alin meteorite were scattered over a large territory, some of them lying several score kilometres apart. The larger ones were not slowed down so much in the lower atmosphere and they hit the ground at speeds of several kilometres per second. The smaller fragments landed at speeds of hundreds of metres per second. The larger fragments exploded on impact, creating big craters. Medium-size fragments penetrated deep into the ground, while the smallest and slowest ones were found lying on the surface. Many of the big fragments exploded, but their speed was evidently not enough for vapourization. The craters abounded in meteoritic material, mostly finely shattered, with several large fragments. Significantly enough, the largest craters did not contain big fragments, which had exploded. On the other hand, smaller craters contained many big sizeable fragments that had not exploded.

The Tunguska meteorite may have disintegrated in the air like its Sikhote-Alin counterpart. This seems all the

more plausible as its velocity of entry is estimated to have been 40 km/sec. Another possibility is that both meteorites actually consisted of several chunks, which were dispersed by the resistance of the air and the high temperature. The powerful shock wave travelling in their wake did not disappear at once. It has been calculated that the shock wave could have travelled on until it hit the earth. The resulting impact felled some trees and stripped others of their branches. The force of the impact on the surface was so great that it generated the seismic wave that was recorded by many seismic stations. The rebound of the shock wave into the air generated a sound wave, which also circled the globe and was registered by several weather stations equipped with barographs. Whether this was in fact the case will have to be verified by further investigations.

EXPLOSIONS AT WORK

One usually associates explosions with war, the wail of falling bombs and deadly minefields. At the same time, of course, it hardly comes as a surprise to know that explosives and blasting are widely used in the most peaceful of human undertakings.

Blasting is used in mining. Deep narrow holes are drilled and the explosive is placed at the bottom. The blast loosens coal from the seam and it can be loaded and carted away. The expenditure of explosive material is no more than 100 grams per ton of coal produced.

Blasting is used in preparing the right of way for new roads through swamps and hills. In marshy terrain a blast loosens the top vegetable layer of the swamp on which the roadbed is heaped. The roadbed gradually sinks, pushing the ooze aside. At the required time another row of charges is exploded which throws out the quick clay of the bog from under the roadbed, and the latter settles on the hard bottom. Blasts dig tunnels and trenches through granite and basalt hills.

Blasting yields hundreds of thousands of tons of additional oil from low-debit wells. A "torpedo" is lowered

into such a well and exploded in the oil-bearing stratum. The blast shatters the surrounding native rock and makes way for the oil to flow to the well.

Blasting can even be used to drill wells. The method is a promising one. Ampules containing an explosive are carried in the flushing solution down the well, where they explode upon contact with the well bottom. The blasts loosen the rock, which is carried up by the solution, and the well sinks deeper and deeper.

Blasting is used to clear away ice jams on rivers and to remove tree stumps, in mineral prospecting and the extraction of peat. In recent years blasting has been used in engineering for so-called explosive forming in which metals are shaped or modified to a high accuracy of finish.

Of considerable interest is the use of so-called transmitted blasting. It was once thought to be quite impossible to control the motion of masses of rock hurled up in a powerful explosion. Scientists and engineers discovered, however, that the apparently chaotic motions of turbulent hot air and shattered rock obey strict laws, knowledge of which can bring explosions under control. Today engineers carry out transmitted blasting in which the exploded rock falls in a specified place. For this two rows of charges are laid in the ground. The first row loosens and throws up the rock, the second, more powerful blast, which is let off a second or two later, hurls the rock in the required direction. The first transmitted blast was carried out some twenty five or thirty years ago. Since then the technique has been widely used in digging foundation pits, channel clearing and other work. The biggest transmitted blast in the Soviet Union was carried out 160 kilometres from the town of Krasnoyarsk to strip a coal opencut. Four series of charges weighing a total of 1,860 tons ejected 391,000 cubic metres of rock, making a ditch 20 metres deep, 400 metres long and 85 to 125 metres wide.

Transmitted blasting may be used to erect an earthen dam. The charges are placed in such a way that the masses of earth hurled into the air collide and fall across the river channel. Outside of the necessary preparatory work, it takes practically no time to literally throw such a dam across a river with a minimum expenditure of manpower.

In 1948, the river Angren, in the Soviet Republic of Uzbekistan, broke through the protective dikes containing it and rushed into the fields, threatening to flood villages, cotton plantations and wineyards. By means of transmitted blasting engineers barred the water with a 13-metre earthen dam erected in the several hours needed to deliver the explosives and plant the charges. A total of 12 charges weighing 50 tons were used.

In the end of the 19th century, Charles E. Munroe, an American metal engraver, began experimenting with explosives in his work. He first used a small blast to press an engraved plate into a metal plate blank and thus duplicate the engraving. Then he found that when letters are inscribed on the base of an explosive charge, an exact image is engraved in a metal plate upon which the charge is detonated. It appeared that the impact of the expanding gases was greater at the very points where the explosive was farther from the metal plate. Munroe could offer no explanation for his so-called shaped- or hollow-charge effect.

Take a glass of water and let a single drop fall on the surface. You will notice that a tiny squirt shoots out at the point where the drop fell. The falling drop makes a small hole in the surface of the water. The water that converges into the hole collides in the middle and the kinetic energy of the splash shoots out the squirt. This is the simplest example of the shaped-charge effect. When a hollow is made in a lump of explosive the converging gases collide at the centre of the hollow and produce a thin jet of gas whose velocity is much greater than that of the converging gases. This gas jet easily attains a speed of 8-9 km/sec and develops a pressure of 500,000 atmospheres. Small wonder that it can pierce armour and concrete.

The force of the hollow-charge jet can be augmented greatly if the cavity is lined with a thin sheet of metal. The action of the liner is explained as follows. Let two jets of water impinge at an angle. Two new jets will result: the larger one moving in the plane of symmetry of the two initial jets and in the same direction, and the smaller one in the opposite direction. The total momentum of the resultant jets is equal to that of the initial jets.

Now, with the jets impinging at a small angle, let us bring them closer together. The point of intersection shifts rapidly towards the nozzles. The velocity of the smaller resulting jet will be greater by the speed with which the point of intersection is moving; the velocity of the larger jet will be less by that value. In the case of a lined hollow charge, the pressure of the explosive, which is hundreds of thousands of atmospheres, drives the liner inwards. At the point where the liner, moving rapidly along the axis of the cavity, converges it behaves like a fluid, moreover, like a compressible fluid (the density of the metal at the convergence point increases by 20-30 per cent). This "metal fluid" separates into two jets, one of which ejects forward at a great speed. The jet in the opposite direction has a much greater mass but a much smaller velocity, which is practically zero. In practice, therefore, only one jet extrudes and all the kinetic energy of the moving metal passes to a small portion of the liner. For example, if the metal lines a cone diverging at an angle of 12 degrees, only 10 per cent of the total mass of the liner will go into the fast jet. The energy density in the jet is thus ten times higher than in the whole of the metal driven towards the centre of the cavity. The mean velocity of the jet is more than three times that of the liner, which is several kilometres per second. The jet may therefore have a velocity of more than 10 km/sec. What takes place is a concentration of energy in a small mass of matter.

By making cones with very small angles of divergence and lining them very thinly with a light metal like beryllium, it is possible, by dint of a few technical subterfuges, to achieve jet velocities of as high as 100 km/sec. Shaped-charge techniques have been used in high-altitude meteorological rockets to investigate meteoritic phenomena.

When a shaped-charge jet impinges on an obstacle with a speed of tens of kilometres per second it develops pressures of millions of atmospheres. In 1944, Lev Landau and one of the authors of this book calculated the action of highly converging detonation shock waves. If the wave originates at the surface of a spherical hollow charge and travels inwards, the pressure in the wave in-

creases approximately inversely as the distance to the centre. If the charge is big enough huge velocities are obtained and a large volume of gas can be compressed to tremendous pressures.

The use of converging waves for obtaining high concentrations of energy in relatively large volumes of a medium has been applied in engineering and in attempts to produce thermonuclear reactions. Tamm's and Sakharov's studies of cylindrically converging plasma were based on investigations of converging shock waves. The faster the energy output in an explosion the more shattering the blast. A TNT cartridge can burn in the air without any danger of exploding. In fact, during the war the men at the front would often use TNT from defused enemy mines to heat their dugouts. But woe if a fuse found its way into the stove! The tame burning would instantaneously develop into an explosion, the iron stove would be torn apart and the dugout door knocked open by the blast wave. What had happened to turn the apparently harmless fuel into a dangerous explosive?

Imagine a pipe filled with a combustible mixture, say methane and oxygen. If we ignite the gas at one point of the pipe the flame front will travel in both directions. When combustion begins the signal of the event travels through the gas that has not yet been involved with the speed of sound. As a result the ignition of a neighbouring layer takes place in somewhat different conditions: a weak shock wave has passed through it, compressing and heating it slightly. But at higher temperature most chemical reactions take place faster, therefore the new layer burns somewhat faster than the initial one. The burning of the second elementary gas layer builds up the shock wave a little more and the third layer starts burning at a still higher initial temperature. The combustion proceeds still faster, and so on, accelerating sharply from layer to layer. From a rate of several centimetres or metres per second the combustion front accelerates to several hundreds or even thousands of metres per second within fractions of a second. The velocity of the combustion front increases until it equals the velocity of the shock wave caused by the combustion. Any further increase of the velocity is

impossible as the combustion takes place at the shock wave front. The process of combustion at the front of a shock wave is called detonation, and a shock wave at whose front energy is evolved is called a detonation wave. For conventional mixtures of combustible gases the detonation wave spreads at a velocity of several kilometres per second. If the initial gas pressure was equal to atmospheric, the final pressure builds up to several tens of atmospheres. An increase in the initial pressure brings about an increase in detonation speed and pressure.

In explosives containing oxygen, which supports combustion, detonation occurs somewhat differently than in gas mixtures. Detonation is initiated by a primary impulse provided by a detonator fuse or primer made of a high-speed explosive. In the explosion of the primer, which is in contact with the explosive, there occurs a rapid evolution of energy and a pressure jump of several thousands or tens of thousands of atmospheres. The pressure impulse is transmitted to the explosive charge, a shock wave passes through it, compresses it and reduces the distance between its molecules and atoms. The explosion occurs at the shock wave front, where the detonation wave coincides with the shock wave. In many explosives pressures of several hundred thousand atmospheres develop at the detonation wave front.

We still know very little about the physics of exploding stars—novae, supernovae and pulsating stars. We can surmise, however, that in some of them a detonation wave mechanism comes into play. The evolution of energy due to nuclear reactions, which begins at the enormous pressures present in the middle of a star, generates a shock wave that immediately turns into a detonation wave. It raises the pressure and temperature, which had been insufficient for sustained nuclear reactions, and this further contributes to the rate of explosion of the detonating star.

In recent years scientists have undertaken extensive studies of the physics and technology of transmitted blasting and shaped-charge phenomena. The aim is to learn, to control and effectively harness the destructive forces liberated in explosions. Man is ambitious. Already today he

is contemplating explosions on a cosmic scale. Professor G. Pokrovsky has suggested a project of turning the earth as a whole into a huge spaceship which, if the need arose, could be propelled out of the solar system into cosmic space by the reactive force of a series of thermonuclear explosions at the South Pole. Another project envisages the transfer of planetary satellites by employing the force of matter-antimatter annihilation. The reality of ten thousand years hence may be much more ambitious than our wildest dreams and men of the future may yet learn to use the power of explosions to reconstruct whole galaxies as they see fit.

Biography
of the universe

Explosions of incredible force take place on the surface of the sun

THE DAY OF CREATION

Imagine a race of intelligent beings whose life span, from birth to death would be no longer than the duration of a flash of lightning. To them all the observable events of our world would be as an instantaneous snapshot is to us. They would see the inhabitants of our world as creatures in a variety of incongruous postures. They might, for example, observe a human being suspended apparently motionlessly over a cinder track, legs spread, mouth gaping and eyes staring: to us this would be a sprinter setting a new speed record. Other men would appear to be perched motionlessly—and silently—in the stands of the stadium, though we would say that they were rooting in the sportsman at the top of their lungs.

By collecting experience these short-lived beings could, of course, detect the runner's motion, extrapolate his path and determine the relative displacements of different parts of his body. But it would take many genera-

tions to record observations and study ancient manuscripts (dating back hundreds of generations) to draw a picture of the event at the stadium. How incredibly difficult it would be for them to gain a correct impression of the life of human society and, the more so, its past history!

This is precisely the position man finds himself in when studying the evolution of the universe. Nebulae hurled apart by a titanic superexplosion swirl in huge eddies, whirlpools of galaxies race apart, planetary systems are born, gaseous nebulae and galactic systems collide. But the astronomer who spends a life-time peering into the eyepiece of his telescope and developing photographic plates sees one and the same picture: the runner poised motionlessly with his legs spread over the cinder track. Years of human life are no more than fleeting instants in comparison with the tens of thousands of millions of years which one leap of the universe lasts. The scientists' task is to provide feasible explanations for the various items in the photograph.

One way, of course, is to gather facts, make precise measurements and wait, wait and wait until future generations of earthmen will be able to compare our snapshots with theirs and determine the motions of gas vortices in nebulae and stellar vortices in galaxies from the microscopic changes in their positions. This kind of work is undoubtedly necessary, but equally undoubtedly it is inadequate, and new ways and means of studying the universe must continuously be devised. By studying sound waves our imaginary short-lived beings could establish that they are due to the shouts of the audience in the stands. By analyzing the runner's path they could establish the existence of gravity. In the same way men detected the fleeing galaxies by the red shift and determined the age of the earth on the basis of the relative quantities of uranium and lead in indigenous rock. And scientists will, of course, make many new discoveries explaining the contents of the instantaneous snapshots of the universe at their disposal.

It is already possible today to form an idea of the part of the universe which lies within reach—no, not of obser-

vation, but of mathematical analysis. For mathematics is capable of penetrating much further than the best telescopes. The resulting conclusions, however, are as yet purely hypothetical and cannot even be called theories. Some hypotheses have been rejected, others will enter the treasure-trove of science. They emerge at the front line of science where opinions diverge, views clash and new information is continuously being accumulated.

Let us sweep the dust from our imaginary time machine and undertake another distant journey—millions and thousands of millions of years into the past.

It is pitch black. The space about us is not necessarily like the one we are accustomed to. For space is a form of existence of matter and its properties change with the changing properties of matter. The structure of space varies, for instance, depending on whether it contains large or small masses of matter, which affect its curvature. But how can space curve? And what, as a matter of fact, is meant by space curvature? The concept is involved and not easily pictured. This can only be done by an analogy with things more familiar.

A giant cannon, like Jules Verne's Columbiad, shoots a projectile vertically up into the sky. The projectile emerges from the muzzle and flies up in the earth's gravitational field. It gradually slows down and then falls to earth. We can replace gunpowder with a more powerful propellant, tilt the gun at a small angle to the horizon and shoot our projectile into orbit around the earth. The earth's gravitational field deflects its path and closes it into an ellipse. We again increase the charge, the projectile's speed tops 11 km/sec and it leaves the earth for good. Will it fly away into infinity? If space is a void, yes. But space is filled with matter, and a sufficient concentration of matter may curve space so that neither our imaginary projectile, nor a ray of light (that is, a stream of photons), nor a gravitational wave could ever escape beyond certain limits. The aggregate mass of matter will draw them back. It is this hypothetically closed-in region of space that we call our universe. Evidently, it possesses a certain mass. What happens to a ray of light shot by a star into outer space much like a projectile shot by Jules Verne's Colum-

biad? If the mass of the given part of the universe is great enough its gravitational pull will bend the beam, insofar as it is a flux of material particles, which obey the laws of gravity in the same way as the Columbiad projectile. The greater the mass of the universe the steeper the curve, and the beam may well close in on itself just as the trajectory of a projectile shot from earth at a speed of 8-11 km/sec. Such a closed-in universe is nevertheless infinite in space and one can compute its radius, the radius of the path followed by a beam of light travelling into infinity.

We know that the shortest distance between two points is a straight line. In a curved space a beam of light reaching us from another galaxy has travelled along a curve, which nevertheless represents the shortest line from the galaxy to the earth. Scientists describe the properties of curved space by means of formulas. People uninitiated in the intricacies of higher mathematics must envisage complex physical concepts (which have definite physical meaning) by the method of analogies.

Imagine a two-dimensional world in which the two spatial dimensions are length and breadth. Such a world could be like a table top. The two-dimensional inhabitants of this flatland would have only two coordinate directions and they would not have the slightest idea of a third coordinate. Evidently, in studying their universe they would soon find that it has an end, terminating on all sides with a very strange kind of space quite unlike anything in their two-dimensional flatland. But flatlanders could also inhabit an infinite two-dimensional world: a spherical world, which has no end. By speculative reasoning supported with mathematical formalism the flatlanders could determine the radius of curvature of their universe—the radius of the sphere—and come to the paradoxical conclusion that the shortest distance between two points is not a straight line after all. For as long as the flatlanders knew only a small part of their sphere's surface they would fail to notice its curvature, and their geometricians would discover the great axiom that a straight line is the shortest distance between two points. As their civilization progressed, however, they would learn to measure longer

distances and find that the shortest distance between two points is not in fact a straight line.

A sphere is not the only possible closed two-dimensional "universe". Cut out a strip of paper an inch wide and paste the ends together. You will have two closed parallel "universes". A beam of light travelling in any of them would return to its region of space. Twist the paper band once before joining its ends, and you will have a closed one-sided two-dimensional "universe". A line drawn from any point closes in on itself.

To return to our imaginary projectile, a universe closed in on itself by its gravitational field is but one of several possibilities. One might imagine a universe in which the gravitational field is so strong that it decelerates a beam of light to a halt, just as the earth's gravitational field causes a projectile travelling at less than 8 km/sec to return to earth. This, however, is impossible, and the speed of light is, as mentioned before, a universal constant. What can be imagined, however, is that in overcoming gravity photons gradually lose their energy, and light "reddens". Finally, at some infinite distance the photons' energy drops to zero, and light "dies". This maximum distance to which a ray of light could reach would trace the outer confines of the observable universe. It would be an infinite universe, for one could never reach its boundaries.

Finally, one could picture a beam of light as neither "aging" nor being bent by the gravitation of the universe. It travels unchanging in a straight line. This would be an infinite universe in the simplest—and most incorrect—sense.

It seems most likely, and this follows from the equations of general relativity, that the known part of the greater universe, "our" universe, is a region in which the masses of matter cause light to close in on itself. The size of this part of the universe is continuously increasing owing to the "fleeing" galaxies and the resulting reduction in the density of matter and, consequently, gravitational force. The sparser the occurrence of matter in the universe, the less the curvature of space and, hence, the greater the radius of curvature.

Be it noted that in the greater universe, infinite and unbounded, there may be an infinite number of closed universes, expanding, like ours, or contracting, and possibly other formations of which we know nothing and all of which interact.

Now, how will space and our universe appear to us from the vantage point of our time machine, which has taken us ten thousand million years back? On the basis of the velocities of the "fleeing galaxies" some scientists come to the conclusion that at about that time all the matter in the known universe was concentrated in a relatively small region. Whether it was matter as we know it today is a moot point. It may well have been in some unknown form. It may have represented a huge "embryo" in which the incredible pressure at the centre produced not only the nuclei of elements but the elementary particles comprising them as well. It may have emitted photons and gravitons in great quantities, but the fields interacted with themselves and the photons circled in closed curves describing the boundaries of the universe as they were then. All this is pure conjecture.

How did this "cosmic egg" appear? As a result of the gravitational collapse of huge clouds of dust and gas? As a stage in the evolution of matter from forms unknown to us? Science is still unable to answer these questions.

To continue the hypothesis, the build-up of energy at the core of the "cosmic egg" caused it to explode. The shock wave reaching the peripheral strata caused them to expand. Matter became less concentrated, gravitons and photons began to escape from the clutches of the mighty gravitational field, and streams of intense radiation erupted into the void to herald the birth of the universe in which we are living today and whose mysteries we are probing.

All that followed that first wave—clots of matter and beams of light—moved slower, as they were no longer moving in a void but through space filled with fields and matter (only in vacuum does light travel with the limiting speed). Clots of matter swirled outward in whorls and eddies from which emerged the galaxies, our Milky Way included.

But, the inquisitive reader will quickly point out, if this is in any way a true picture of the birth of our universe then it is neither eternal nor infinite, it had a beginning and will have an end. Undoubtedly so. Everything in the world has a beginning and an end. Birth and death are the destiny of people, planets, stars, galaxies and universes alike. Infinite only is the matter of the whole infinite universe which goes through endless changes, eternally evolving and never passing along one road twice.

THE FAMILY OF PLANETS

Let us board our time machine and trace the evolution of the solar system from the "day of creation" to our time. Through millions of years we pass in search of the Milky Way, one of a myriad of fleeing galaxies. Here it is, and here is the neighbourhood where, according to our estimates, the sun ought to be. Instead, however, we see a dark opaque cloud of dust and gas. Glowing through the dust is a dim, red sun, like the warmless disk which dips behind the horizon at sunset. Its brightness increases as we come nearer until it becomes a hot bluish-white star. Its heat vapourizes the dust particles which come too close, and the pressure of its light hurls back the atoms and molecules of the vapour. The space immediately around the sun is swept clean of matter.

But where are the planets? Well, when some day earthmen arrive at a strange star they will not immediately detect the planets circling it—several small specks weaving in and out an unfamiliar pattern of stars. In the case of the primeval sun we at least know the orbits of the various planets. But the earth is not yet there: it is yet to be born. We switch on the motors of our time machine to trace the evolution of the solar system.

Have you ever seen a motion picture in which a beautiful rose unfolds from a bud before your very eyes? This is achieved by means of a simple technique: a cine camera is aimed at a living bud and one frame at a time is exposed every half an hour. When the film is run through a projector at normal speed one sees the beautiful flower burst forth in all its glory.

Our time machine enables us to see the evolution of the dust and gas cloud by compressing millennia into fractions of a second. Myriads of particles travel in various paths through the cloud. They collide, coallesce or, as the case may be, split into several parts and explode into cloudlets of rapidly cooling plasma. A careful scrutiny soon reveals a definite pattern in the apparent chaos of motion. Gradually the spherical cloud compresses into a huge flat disk in the plane of the sun's equator, with the sun at the centre. It is several thousands of millions of kilometres in diameter and only several thousand kilometres thick. The disk is not homogeneous: the inner parts, closer to the sun, are made up mainly of particles of substances with a high melting and vapourization temperature. Volatile gases like hydrogen, nitrogen and methane, which had once been present in solid form, were evaporated and pushed back to the periphery of the disk. Thus in our days does the sun heat and vapourize gases in a comet head and push them back with its beams to form a spectacular tail. As the comet recedes from the sun the gases freeze again and condense on particles of solid matter.

As we move forward in time we notice that more and more particles tend to coalesce than to rebound in collisions. Soon observable condensations of nuclei with appreciable gravitational attraction appear. Smaller nuclei revolve around many of them. They collide, some scatter, others coalesce. And there, at last, is the earth. It is only several hundred kilometres in diameter and unable to retain an appreciable atmosphere. Its surface is bombarded by countless meteorites, which adhere to it, and gradually it swells like a big ball of snow being pelted with moist snowballs. As it increases in size new phenomena develop. An atmosphere grows around it and a stratification of matter takes place within. Heavy particles sink towards the centre, light ones float up. The growing pressure inside causes the core to heat—not very much, only to several hundred, at most a thousand, degrees above absolute zero.

In the same way other planets form out of the ring of gas and dust. Practically the whole matter of the original cloud has gone into their formation, and the sun

with its new family of planets shines brightly in the cleared space.

The dimensions of the solar system, the planets comprising it and their orbits have been measured in considerable detail, the planets have been "weighed". The information has been arranged and systematized, and some general conclusions can be drawn:

—the solar system is a system in the literally sense; it is not just a haphazard collection of planets;

—the planets all lie in approximately the plane of the sun's equator;

—they move in their orbits in the same direction, and the sun revolves in the same direction; furthermore, the sense of rotation of all the planets (except Uranus) on their axes is the same;

—the sizes of the planets increase gradually from the sun to Jupiter, after which they decrease. Mars is an exception, but if the mass of the asteroids is added to it it will appear to be in place;

—the planets are spaced at regular intervals following a simple mathematical formula (Bode's law).

Many other features of the solar system confirm that it is hardly an accidental formation and it must have evolved in the natural development of matter according to the laws of physics. Otto Shmidt, a celebrated Soviet mathematician, physicist and traveller, was the author of the first mathematically founded hypothesis of the origin of the solar system—the one we traced in the foregoing journey through time. His theory offers a convincing explanation of most of the observed features of the solar system. Still, some points of it have been subjected to sharp criticism. Notably, the very first stage in the evolution of the solar system—the "capture" of a dust cloud by the sun—has not been well grounded. Obviously, the only way the sun could capture such a cloud of dust and frozen gas was to pass through it in its path through the universe and entrain part of it. This is what Shmidt has suggested. The critics of his theory, however, have presented mathematical proof that this could not have happened, and if the sun would meet a cloud of gas and dust it would simply pass through it and emerge as "undusty" as be-

fore. Shmidt and his supporters, on the other hand, claim that, due to collisions of particles inside the cloud, the entraining could take place. This would also be possible if the sun met a star while passing through the cloud.

The argument continues. As we see it, it is wrong to detach the origin of the solar system from the origin of the universe. Surely, there is no reason to suggest that the sun appeared first and only later the planets came into being. Much more logical would be to suppose that the solar system as a whole originated at the same time.

A gigantic explosion splashed huge drops of matter in all directions. These condensed around denser lumps of matter into stars. In this process one could naturally expect surrounding gas-dust clouds to swirl in eddies. Various particles in the cloud would naturally have different angular momenta, or simply different speeds. The faster particles would not fall towards the centre of gravity and would continue to move, collide and coalesce with other particles, gradually building up into planets possessing considerable angular momentum. The great angular momentum of the planets thus appears as an inheritence from the gas and dust particles of the primeval whirlwind.

The slower moving particles collapsed towards the centre of gravity and went into the making of the sun. As their angular momenta were small, the sun's angular momentum is also small and it revolves relatively slowly on its axis.

This hypothesis, it should be noted, does not preclude the possibility of stars and planets forming out of dust and gas eddies and nebulae today. The evolution of matter is continuing, and what happened to the sun and planets thousands of millions of years ago may well be taking place today in another part of the Milky Way or in other galaxies.

Much remains unclear in the cosmic history of stars and planets. We have mentioned that Shmidt's theory is based on the firm foundation of formulas and calculations. But they, too, are not final or absolutely clear. For example, Shmidt and supporters of his theory did not take into account the effects of electromagnetic fields in the "act of creation", which could presumably be consid-

erable. When these are taken into account Shmidt's theory may well turn from a mathematical into a purely speculative one. On the other hand, failure to take account of electromagnetic effects may well be responsible for its weak points and consideration of them may close its flaws and loopholes. Scientists are only making their first steps in the hydrodynamics and magnetodynamics of outer space and much remains undiscovered and unknown. One thing, however, can be said for sure: the universe will not remain a frozen instantaneous photograph. Man will bring it to life. He will write the biographies of stars and galaxies, just as he is writing the story of life on his native planet.

ONE TURN OF THE SPIRAL

Many, many episodes in the earth's history are as unknown to us as its birth. A man's wounds may tell us that he has participated in many campaigns and battles. But even the most attentive scrutiny of old scars offers no indication as to his courage, or where he fought, or on whose side. Our planet's face also carries the scars of many old wounds due to unknown causes.

The numerous lakes of Finland and Karelia are scars left by the glaciers which, in the last several million years, descended several times from the hills of Scandinavia almost to the Mediterranean sea, only to recede north again. What caused the cooling of large areas, possibly even of the whole of the planet? Scientists have no answer to the question although the glacial periods are fairly recent events in the earth's history.

In Antarctica, large deposits of coal have been discovered. Coal is the fossil remains of ancient giant fern forests. Once upon a time virgin tropical forests grew on the southern continent, giant dragonflies flitted in the sun and life thrived in marshy lagoons. Snow-covered Spitzbergen Islands, where coal is being mined extensively, also once enjoyed a tropical climate. What caused the cooling which has covered the South Pole with unmelting snow and the Arctic Ocean with unmelting ice? This is another riddle in the earth's history.

The earth is several thousands of millions of years old. Paleontologists date life back no more than a thousand million years. Why did it appear so late? Maybe this thousand million years is just the latest outburst of life which had originated much earlier and was wiped out by some cosmic catastrophe: an outburst of the sun, the deadly radiation of a passing star or some cataclysm of purely terrestrial origin?

What are the prospects for the forseable future? Can mankind discount the possibility of a cosmic accident? The answer to this appears to be yes. The sun seems to be a sufficiently stable star, with a constant intensity of radiation and any sharp reduction or outburst is highly improbable.

The history of mankind from the most ancient cultures to the present day spans hardly more than ten thousand years. It can easily be assumed that in another ten thousand years the destinies of humanity will not be tied up so irrevocably with the earth as they are today. Man will undoubtedly migrate not only to other planets of the solar system but to neighbouring stars of the Milky Way as well.

What will the earth, the solar system and the universe be like in several thousands of millions of years? Can we travel in our time machine as far into the future as we did into the past? The answer is no. Such distant vistas are much to obscure, we know too little about the laws of nature and have too vague an idea of the evolutionary paths of matter. However, several considerations of principle can be made.

First of all, the concept of the recycling evolution of matter is utterly insolvent. According to this theory, stars form out of nebulae of gas and dust, then they cool, then dissipated energy condenses in some unknown way, stars collide, explode and turn back into gas and dust, and it all starts over again. Today we can say that if such a recycling of matter does occur—and on a certain scale it does—it is not dominant or determinative in the evolution of matter on the universal scale.

There is also the "nonrecycling" theory of the "heat-death of the universe". Imagine two cylinders of gas,

one hot and one cold. If we mix the two gases the mixture will be neither hot nor cold. It will be warm, the temperature being the average of the two extremes. This is obvious, just as it is obvious that one cannot separate the gases into the cooler and hotter ones again and that it is impossible for one side of a room to be cooler than the other without external interference. In natural processes temperature eventually tends to level off. Formulation of this principle gave rise to a question of interest to physicists and philosophers alike.

If all temperatures tend to level off, why do high-temperature stars exist alongside cold cosmic bodies? Why are the temperature extremes of the universe so great? Is this proof of a primeval impulse which brought huge sources of concentrated energy into being, and of the fact that now a levelling off is taking place? The first to attempt to answer this question was the famous physicist Ludwig Boltzmann. Boltzmann studied the kinetic theory of gases and matter and formulated the basic principles of gas dynamics and kinetics. He established that the molecules comprising a gas have different velocities. Most of them move with more or less the same speed, which determines the temperature of the gas, but at each instant there are always present some relatively slow- and fast-moving molecules.

Imagine a gas consisting of only ten molecules, five moving faster than the mean, and five slower. With so few molecules it is quite possible that at some moment all the fast molecules will gather on one side of the room and all the slow ones on the other. The probability, though not very great, is not altogether impossible. This means that motion in the gas can take place not only in the direction of a levelling off of the temperature but also in the direction of creating a temperature drop. Natural processes opposed to the levelling off of temperature, processes in which temperature differences develop, are due to statistical fluctuation phenomena. Undoubtedly, small fluctuations occur continually in gases and one could always find small regions and groups of molecules where the temperature is above the average.

Boltzmann suggested that the observable universe re-

presents a gigantic fluctuation within the greater universe, which faces the prospect of heat-death, that the observable universe is a "group of molecules" with a momentarily "higher-than-average" temperature. Boltzmann's conception was of a progressive nature, but it did not win many adherents. It was debated heatedly, but the arguing sides overlooked one important consideration: the investigations of experts in gas kinetics deal with the microcosm of gas molecules. But the universe is not all made up of hydrogen molecules—it contains many different molecules and atoms. Can a conclusion drawn from the study of gases be extended to the whole of the universe? Of course not, and for that reason Boltzmann's ideas and the conclusions of the exponents of his theory were erroneous.

Only Einstein was right when he wrote, without laying claim to the comprehensiveness of his investigations, that it was hardly reasonable to extend the laws of finite matter to the infinite universe. Investigations of the finite universe yielding general ideas about matter and the laws of motion can be applied to develop very general and approximate premises concerning processes involving the infinite universe.

Is the pessimistic conclusion concerning the inevitable "heat-death" of the universe at all valid? There is a branch of mathematics, known as set theory, developed by the

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Mathematically speaking

THE "HEAT-DEATH"

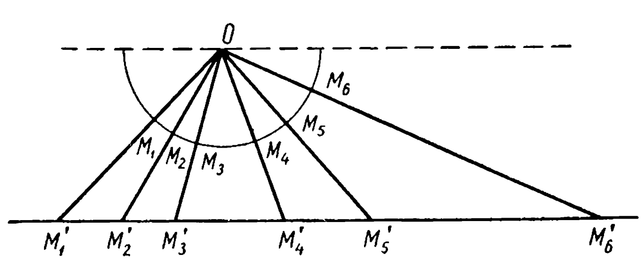
Insofar as in investigating the general state of matter in the universe one must deal with an infinite variety of particles, a knowledge of some of the most general properties of certain infinite sets is essential.

The simplest infinite set is the set of positive integers 0, 1, 2, 3, 4, 5, ..., *n*, where *n* tends to infinity. This is a so-called countable set. Note that the set 1, 10, 100, 1,000, 10,000, 100,000, etc., is also countable and that the numbers of the first and second set can be put into one-to-one correspondence. For the numbers of the second set can be written down in the form 10^0, 10^1, 10^2, 10^3, 10^4, 10^5, etc. This is one of the paradoxes of infinity. A countable infinity is the weakest of all infinities. For example, an infinite set of positive integers cannot be used to count all the points on a

19th-century German mathematician Georg Cantor. It studies sets of infinite numbers of particles, integers, letters, or other elements. Being a theory which attempts to penetrate the laws of infinity, it draws some interesting conclusions which, if applied to physical laws, might be able to answer the question as to why the universe appears to be eternally unbalanced. These conclusions are very complicated and can therefore be considered only in the most simplified form.

We have noted on several occasions that the greater universe is nonhomogeneous in composition and contains an infinite number of infinitely diverse particles. It contains interstellar gas consisting of ionized atoms of hydrogen with admixtures of atoms of other elements, comparatively small-sized lumps of solid matter like meteoroids and asteroids, large lumps of planets, giant spheres of plasma—stars, stellar systems, galaxies and vast domains like the observable universe which are described by Einstein's formulas. Each such formation contains a virtually infinite set of "lower" elements: asteroids are made up of molecules, the universe of galaxies, etc. For the energy of the infinite elements comprising the universe to level off, all of them, from the last ionized atom of interstellar gas to the greatest galaxy, must interact with an exchange of energy.

One of the conclusions of set theory states that, even given an infinite period of time, all these infinite interactions can never take place. (The conclusions arising from an analysis of this problem were published in 1949 by one



of the authors of this book, Kirill Stanyukovich.) The reasoning can be understood from a simple physical interpretation, namely that thermal equilibrium could be achieved only in a universe that is a uniform continuum, like a gas or jelly. A universe made up of elements ranging from minute particles to huge aggregates of matter capable of attracting smaller elements can never achieve thermal equilibrium. For matter is energy in concentrated form, and regardless of how much it is dissipated as electromagnetic or gravitational fields, the reverse transformation of gravitons and photons into electrons and other elementary particles is possible, and this means a reconcentration of energy. Once this was established the "heat-death" hypothesis lost its meaning.

When the chaplain of Westminster Abbey was preparing a series of lectures against atheism he asked Newton for scientific proof of the existence of God. Newton, who in the latter years of his life had turned increasingly from science to religion, cited as such an example the need for an initial "impulse" to set the planets in their eternal motions around the sun. The "heat-death" theory also stands in need of such a primary impulse. If all energy processes develop in one direction only, like a river flowing downhill, it stands to reason that the time will come when the mountain of energy will gradually be washed away into the sea. Evidently, then, there must have been a time

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straight line segment. A set of points on any section of a straight line segment, or on an infinite straight line, or in the whole of space, is noncountable, it constitutes a continuum which cannot be exhausted by any counting operations. This is known as "the power of the continuum" or cardinality.

In particular, it is easy to show that in fact to every point of a line segment there corresponds one and only one point on an infinite straight line. Consider a semicircle the length of which is equal to the length of the given line segment. From the centre of the semicircle project all its points on an infinite straight line passing below it. You will readily perceive the truth of the foregoing statement made above.

We can make use of the concepts of countable sets and cardinality to investigate the most general laws of behaviour of the infinite set of particles of matter in the infinite universe.

when "someone" dredged the sea to heap up the mountain of energy. This "someone" must occasionally wind the clock of the universe to keep it ticking.

A hundred years after Newton, the French scientist Laplace outlined to Napoleon the gist of his materialistic hypothesis of the origin of the solar system—a hypothesis that explained the "initial impulse" which Newton could not explain.

"And where does God fit in?" Napoleon asked.

"Sire," Laplace replied, "I had no need for that hypothesis."

It took less than a hundred years to refute the exponents of the "heat-death" theory.

After the enunciation of the general theory of relativity, the theory of the so-called pulsating universe came into vogue. According to this theory the universe periodically compresses and expands. In the course of each pulse the galaxies, stars and planets develop. The energy released at the beginning of each expansion is gradually dissipated in overcoming the common gravitational field of all the masses filling the universe. When it is expended completely contraction begins.

Every year spring comes with sunshine and flowers to replace the winter frosts. Then come summer, the sodden mists of autumn, and again the white blanket of winter covers the land. This is the seasonal cycle, which

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Divide the infinite universe into a countable set of finite domains. Evidently, each finite domain contains a finite number of elementary material particles. To take into account the interaction of matter with the fields for which it is responsible (electromagnetic and gravitational), assume, proceeding from the quantum theory of matter, that a finite domain of the universe contains a finite number of quanta. For the purpose of our reasoning we can also assume that some elementary quanta can be as small as we wish—not in the sense that a quantum is regarded as "point energy" but in the sense that a countable set of such quanta occupies a finite volume and carries a finite energy.

Thus, in our finite volume of space there may even be, not a finite, but a countable set of elementary particles. Hence, in all space there will be a countable set of elementary particles.

Evidently, a set of interac-

repeats itself over and over again just as the earth circles the sun in its orbit again and again. Yet no cycle is an exact repetition of the previous one. Each new spring is in some way different from the one before. The seedlings in a young grove have grown taller. A mighty old tree has decayed and toppled over. Erosion has undermined an overhanging cliff, and sandbars in a river mouth have grown bigger. These are doubtlessly trifling events in the great cycles of nature, but the accumulation of such trifles yields evolution. Mountain slides do not change the mountain landscape very much, but geologists know that whole mountain ranges have been worn down by wind and water, which leave hardly a trace of their work from day to day.

The circle of seasonal changes is actually broken: it is rather a spiral, with repetitions always occurring on a higher and higher level. Even the earth's orbit around the sun is a closed ellipse only when we do not take into account the sun's motion. The sun itself participates in the rotation of the Milky Way and in the Milky Way's flight through the universe. The resultant motion of the earth is complex indeed. It stands to reason, then, that even in a pulsating universe no two pulses can be absolutely identical. It is impossible for all processes to be reversible. In the long run changes in quantity must lead to changes in kind and a transition to a new state. Can we at least attempt to imagine what such transitions could lead to?

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tions between the particles within each finite volume of space in a finite time interval will be countable, if the particles make up a countable set, and finite, if the particles make up a finite set. In the whole of infinite space there will occur in a finite time interval (for both assumptions) a countable set of interactions. (By interaction we understand any process involving two particles which results in a change of their masses or energies.)

Insofar as any infinite time interval can be divided into a countable set of finite intervals, a countable set of interactions will occur in the course of an infinite time interval in the whole of the universe.

A set of all possible interactions for a countable set of particles represents a set of all the subsets of the given countable set, that is, this set of all possible interactions will possess cardinality.

The continuum of possible in-

Before answering this question let us return from the boundless expanses of the universe to the microcosm of elementary particles. The atom was once considered the smallest, indivisible particle of matter (the word "atom" means "indivisible" in Greek). Then it was found that the atom consists of a nucleus with electrons revolving around it, and these were declared indivisible. Today, in the age of nuclear energy, a schoolchild knows that the atomic nucleus is a complex structure which can be split and transformed. An electron colliding with a positron (anti-electron) turns into radiation whose energy and mass, in accordance with Einstein's principle of equivalence, must correspond to the energy and mass of the colliding particles. In any case, the electron is no longer regarded as a tiny solid ball incapable of further division. As Lenin wrote, the electron is inexhaustible.

Like protons, neutrons and other "elementary" particles, the electron undoubtedly has a complex structure. What we call "elementary" particles are probably some highly compressed substance which can never remain at rest and pulsates incessantly. At least, this conception does not contradict any of the known facts. In such pulsations an elementary particle interacts with the surrounding field. Each expansion "pushes" the field aside, and this causes an expenditure of the energy which is responsible for the field. Does the energy flow back to the particle when it compresses? Probably not always, and the pulsat-

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teractions (states) cannot be exhausted by a countable set of real interactions in any infinite time interval.

Assume (though it is not so), that the whole of the universe is filled with particles of one class, molecules, for instance. Then the set of all possible states possess cardinality. But, the set of independent (unrepetitive) states would be countable, hence in the infinite life span of the universe it would already have achieved equilibrium, or we must assume that we live in a vast unbalanced domain of the universe which formed as a result of a highly improbable process of fluctuation. This is the process in which one could expect all the fast molecules in a region of space to gather at one side, and all the slow molecules, at the other. For a small number of molecules this may occur fairly frequently,

ing particle gradually dissipates energy. This means that it loses mass, that is to say, the mass of an elementary particle is not necessarily constant.

Today, at the present stage in the evolution of matter, an electron's mass equals 9×10^{-28} gram, and a proton "weighs" 1.7×10^{-24} gram. Ten thousand million years ago they were heavier, and ten thousand million years hence all the elementary particles in the universe may "weigh" less than today. The change in mass could affect other properties of elementary particles. This microcosmic process would suggest the nonrepetitive evolution of matter in the universe.

Does the concept of pulsating elementary particles agree with the hydrodynamic theory of gravitation mentioned before? An answer may be found in a theoretical experiment described by Nikolai Zhukovsky, the "father of Russian aviation". Imagine two spheres immersed in an incompressible fluid. If the spheres are made to pulsate synchronously, so that the maximum volume of one corresponds to the maximum volume of the other, they will gravitate towards each other. Moreover, the law of attraction will be expressed by a formula identical to Newton's formula of universal gravitation: the force will be proportional to the energies "radiated" by the spheres and inversely proportional to the square of the distance between them. If the pulsation is not "in step" and the maximum

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but for a great number the probability of such a process is vanishingly small.

To be sure, we could also assume that the universe was "created" a finite time ago, but this is even less likely. The universe, of course, does not consist of one class of molecules, and we must therefore conclude that there is always present in the universe a countable set of classes of different "particles" (elements) such that every "particle" of one class may include "particles" of lower classes. By "particle" we can understand any autonomous formation: a photon, molecule, star, stellar system, etc. We can assume that the infinite diversity of classes of different "particles" is a consequence of the interaction of matter with the fields for which it is responsible. Every "particle" may exist in the universe in any (apparently infinite) number.

A set of all possible interactions of the whole diversity

volume of one corresponds to the minimum volume of the other, they will repel each other with a force given by the same formula.

Obviously, the analogy between pulsating elementary particles in a gravitational field and pulsating spheres in a fluid is remote. But it does offer an idea of the hydrodynamic theory of gravitation. Possibly in the course of this pulsation the elementary particles eject elementary packets of energy in the form of gravitons.

Although the mass of elementary particles appears to decrease, the latest findings of theory indicate that the total mass and energy in our region of the universe is constant. Along with the creation of gravitons there takes place a continuous creation of new elementary particles out of "old" gravitons at an estimated rate of 10^{-45} gram per cubic centimetre per second. This is accompanied by a change in the so-called world constants: the gravitational "constant" increases, the elementary charge and Planck's "constant" decrease. Only the speed of light does not change.

Slowly but surely matter changes from one form into another. A steady accumulation of quantitative changes is taking place which must inevitably develop into a qualitative leap. What kind? With our present knowledge we are unable to say. In any case it will mean an end of our three-dimensional closed universe. It may represent merely the completion of one turn of the evolutionary spiral on an incredibly great scale. Be that as it may, but it will also represent a new stage in the evolution of matter, eternal and indestructible.

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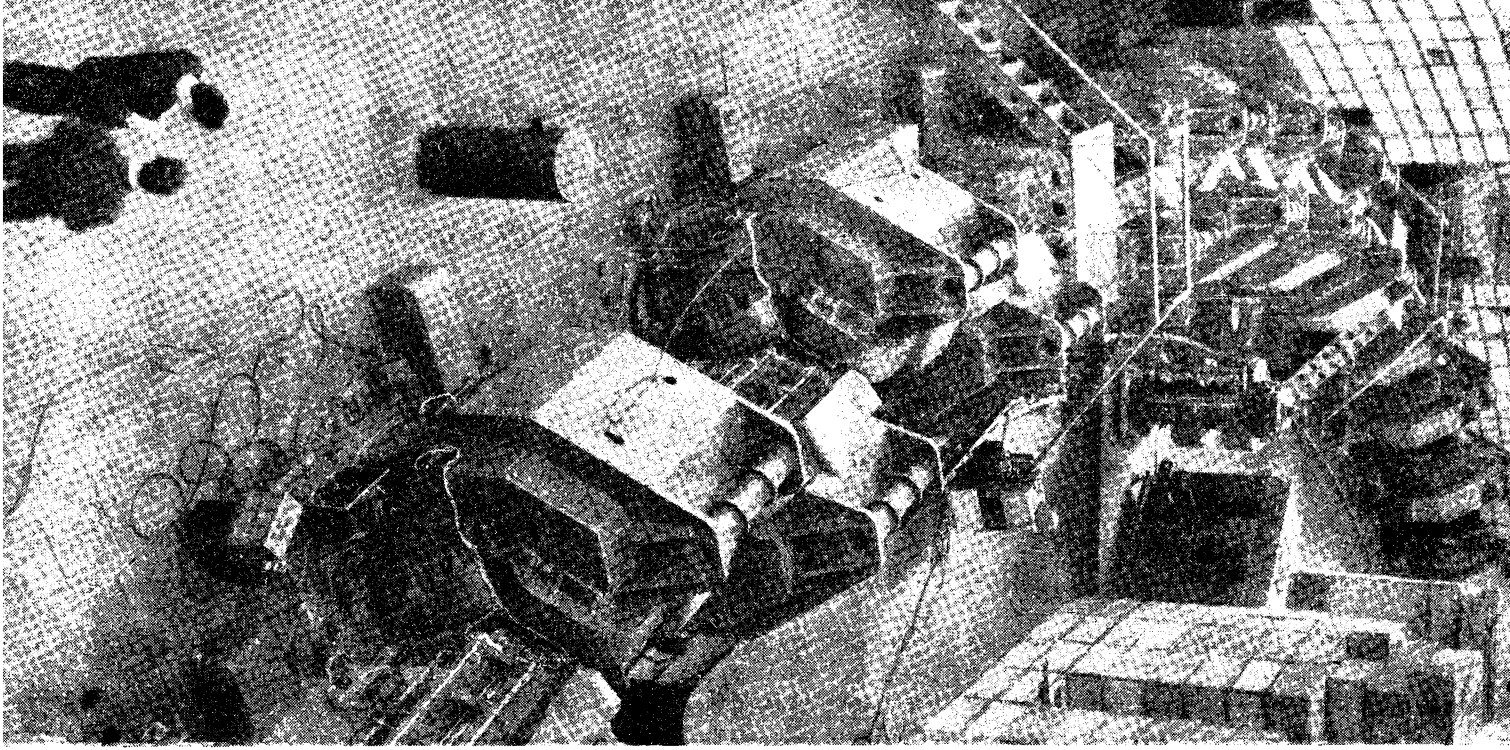
of "particles" without any repetition of state possesses cardinality. Hence the totality of interactions of different formations in the universe cannot be exhausted by any counting operations, which leads to the noncyclic development of matter, and this makes possible its infinite development.

Masters of the universe

(INSTEAD OF A CONCLUSION)



A 7-billion electron volt strong-focussing accelerator at the Institute of Theoretical and Experimental Physics, Academy of Science of the U.S.S.R. Today this is already a conventional tool for probing the secrets of matter

We are coming back to where we began this book: the day is not far off when man, the master of the earth, will leave the threshold of his paternal domicile and begin the conquest of the universe. He will explore and settle neighbouring planets and eventually the whole of the solar system. Then he will take a giant leap to the planetary systems of neighbouring stars. Nor will this be the last step.

Inexhaustible are the secrets of nature and boundless is man's ability to probe them, not only by the speculative reasoning of an observer whose brain encompasses infinite spatial and temporal dimensions, but also as an active explorer, transformer and creator.

Until man appeared on earth life adapted itself to the changing conditions of the environment. The animals and plants which failed to do so perished, and paleontologists find their remains in various geological strata. Man,

on the other hand, from the very beginning began to subordinate nature to his needs. Today he cuts channels through deserts and builds vast irrigation systems, he alters the courses of rivers and creates huge artificial lakes, he contemplates turning ocean streams to warm the Arctic Ocean.

The work of creation and transformation is perforce preceded by the work of cognizing the laws governing the states of matter and fields, the laws of their mutual interactions. In whatever branch of the exact sciences a scientist works he is probing the secrets of matter. Whatever machine an operator drives he is handling matter.

Many are the secrets of the solid state of matter that have yet to be unravelled. People have only just learned to make use of the wonderful properties of semiconductors, which hold promise of power plants capable of transforming sunlight directly into electricity, pocket-size television sets, supereconomical refrigerators and sophisticated air-conditioning systems. Only recently have scientists discovered the remarkable behaviour of some metals at temperatures close to absolute zero—so-called superconductivity. Applications of this discovery are still a matter of the future. Men have only just learned to make diamonds and substances harder than diamond. They have only just produced the first tiny undislocated crystals of metals which are a thousand times stronger than the toughest steel. Still awaiting their discoverers are substances capable of withstanding temperatures of 5,000-7,000 degrees C, substances harder than diamond that could be melted and cast, metals transparent as glass and glass as strong as metals.

The liquid state of matter, too, holds promise of great advances. Scientists have discovered in the ocean deeps a layer of water possessing superconductivity of sound. What is its secret? What applications will be found for the remarkable superfluidity of liquid helium? Engineers in different fields are clamouring for liquids with properties which nature failed to provide: liquids whose viscosity would not change with temperature changes from absolute zero to thousands of degrees, nonevaporating liquids, and liquids resilient as rubber.

Take gases. Are the secrets of the gaseous state of matter all known, have all applications of gases been discovered? Rarefied gases burning noiselessly and coldly in the neon lights of advertisements—is this the only application of the tamed aurora borealis? The destructive sonic boom of supersonic aircraft—are there no useful applications for this phenomenon?

Plasma is an unexplored ocean with undiscovered islands and continents where the secrets of thermonuclear power plants, artificial suns and interstellar flight lie hidden.

Probably even more wonderful is the intangible matter of electromagnetic, gravitational and nuclear fields. The list of undiscovered and unused properties of matter can be continued endlessly. Add to them the miracles that can be worked by making the different states of matter and fields interact in new ways.

Man is still very young. His recorded history spans less than ten thousand years from the most ancient civilizations. Less than fifty years have passed since there emerged on earth a social system throwing open boundless opportunities for man's creative powers, once shackled with social chains. What wonderful exploits will man perform in the near and distant future? Will he alter the inclination of the earth's axis to bring eternal spring to all people? Will he erect a transparent roof over the globe to regulate solar radiation? Will he bring the earth closer to the sun?

However fantastic our dreams may seem, we can be sure that the boldest flights of fancy will one day come true. Man will carry life to neighbouring planets; man will populate the planets of neighbouring stars. His intelligent spirit will reach out farther and farther into the universe. There is no limit to his growth and possibilities, just as there is no limit to the universe.

The antenna of the Prioksky radio telescope is one kilometre long